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ECL 265

INDOOR AIR POLLUTION MIGRATION TRANSPORT MECHANISMS IN HIGH-RISE BUILDINGS

This engineering case treats an indoor air pollution problem that occurred in a high-rise building. It illustrates the air migration problems that exist within high-rise buildings which can act as transport mechanisms for buoyant air pollutants. It also demonstrates some of the air engineering methods that can be applied to prevent or inhibit such migration problems.

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SITUATION

On the 23rd of April 1984, while working on-site at the Washington, DC headquarters of the Environmental Protection Agency (EPA), the EPA Project Officer requested that contact be made with a particular General Services Administration (GSA) building manager. The contact was requested because of a possible health and safety (H&S) problem within another Federally occupied Washington, DC building. The EPA Project Officer had offered assistance to the GSA building manager to help solve, as it turned out, an indoor air pollution problem in the eighteen month old twelve level U. S. Information Agency (USIA) headquarters building at 301 4th St., SW, Washington, DC. This building was privately owned, leased by GSA for Federal use and had been built to the requirements of the Washington, DC building code. It should be noted that the EPA Project Officer had volunteered our services to the GSA on this problem because of his knowledge of our many years of work for the National Bureau of Standards (NBS) and the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) on the interior movement of air, and buoyant suspended gases and particulate matter, and our work at EPA headquarters on indoor air pollution problems.

PROBLEM BACKGROUND

During the 1983-84 winter and early 1984 spring seasons, the GSA building manager had received, via the USIA's Safety Officer (an industrial hygienist), several USIA employee complaints about the quality of the air in their workplaces. Some of these employees were suffering sufficiently to obtain medical assistance. In some cases, letters from the medical doctors treating some of the employees were included with the complaints.

Initially, these complaints were primarily about a "dust problem." Subsequently, the complaints took the form of eye irritation, nose bleeds, sore throats and respiratory problems. Reports of "dead" air in some areas were also received. Included with many of these complaints was mention of cooked or cooking food odors. The odor complaints were reported as being the worst on the 5th

floor. They were also reported as being of a continuous nature on the 5th floor.

While obtaining the above information from the GSA's building manager, it was also determined that:

1. The building had three below grade parking levels.

2. The building had nine above grade occupant levels.

3. There was a fast food restaurant located within the building.

    a. It was located on the first floor of the building.

    b. There was a street entrance to this restaurant.

    c. There was also a lobby entrance to this restaurant.

PRIOR PROBLEM SOLVING EFFORTS

Prior to our involvement, the GSA's building manager had attempted to remedy the situation. Three significant steps had been attempted. The first step was of a remedial nature and the remaining two were investigative in nature.

Step 1

The first step taken by the GSA's building manager was to place the problem before the building owner. As a result, the architectural and engineering (A&E) firm which provided services to the building's owner was consulted about the problem. Because of the several cooking or cooked food odor complaints, the A&E firm decided, without any investigation, that the kitchen exhaust stack from the fast food restaurant, mentioned above, was allowing kitchen exhaust gases to enter the outside air intakes to the building's main HVAC system. The remedy suggested and implemented by this A&E firm was to increase the height of

the roof top kitchen exhaust stack, for the fast food restaurant, by eighteen feet.

Step 2

The second step taken by GSA's building management was to obtain assistance from a senior industrial hygienist from a nearby University Center for Occupational and Environmental Health. This gentleman visited the USIA building in December of 1983 regarding the "dust problem" complaints. An analysis of dust samples obtained in and around the work areas of the complainants indicated that they contained 66% cellulose fibers, 25% synthetic fibers, 6% fiberglass fibers, 2% animal fibers and 1% feathers. Occupants of these work areas had complained of flu-like symptoms and a lack of air circulation. This gentleman revisited the building during February 1984 to further investigate the air problems. At this time, the "dust problem" appeared to have vanished but was replaced by newer complaints of the forms mentioned above. This investigator, using smoke tubes, decided that the air circulation within some of the spaces and rooms occupied by the complainants was "..., in fact, good." He made a very limited "inspection" of the HVAC system. His conclusions were that there were no "obvious causes" contributed by the HVAC system. His main conclusion, based on limited measurements, was that the relative humidity of the building's interior air was less than 20% and, at times, "off the low end of the scale." His report stated that he knew of "no health standards" for relative humidity of interior building air. His report also indicated that the low relative humidity was consistent with some of the reported symptoms, e.g., nose bleeds and sore throats. He recommended that the HVAC system be modified to increase interior air humidity during the heating season.

Step 3

During the period from 7 May to 21 May, the GSA acquired additional temperature and humidity measurements in rooms 504, 516, 517 and 518, which were some of the spaces occupied by complainants. Temperatures over this period in rooms 516, 517 and 518 ranged between 70°F and 85°F, and in room 504 between 72°F and 83°F. In

general, the temperatures were mostly above 75°F. Relative humidity over this same period in rooms 516, 517 and 518 ranged between 12% and 39%, and in room 504 between 12.5% and 42%. Mostly, the relative humidity in these rooms was on the order of 20%. The highest relative humidity recorded in each instance was a single measurement. While these measurements of relative humidity reflect the same low level as found earlier by the industrial hygienist, they were acquired during the mild and wet month of May. Heating requirements should have been minimal, if any existed, and the external relative humidity should have been high, in general.

Transient Construction Effects

It was also determined that some interior construction was still in progress during the 1983-84 winter and early 1984 spring periods. This construction work included work on the HVAC system ducts. This work was still underway at the time of the investigation by the industrial hygienist.

Evaluation of the First Two Steps

It is of importance to point out that neither the professional engineering consultants or the professional industrial hygienist stepped back and tried to look at the entire interior air environment of the building, as a whole. The engineering firm took a quick and easy approach that had virtually no basis, certainly no verified basis. It is not an uncommon thing to find roof exhaust stack gases entering outside air intakes because of poor design. However, it was apparent, in this case, that the engineering firm's recommended corrective measure was an "off-the-top-of-the-head" response. It was not based on an analysis of readily available information or any form of investigation of the complaints and their distribution within the building.

The industrial hygienist did not go beyond the immediate work areas in his investigation. His evaluation of air circulation with a smoke tube in a work area showed that there was dynamic movement of the air in that space, but only that. In the case of his conclusions regarding relative humidity standards in working environments, he

was obviously not aware of ASHRAE's* guidelines for humidity control under various work conditions.

Dust Problem Complaints - In the case of the "dust problem" complaints, the period of time in which they occurred correlated with the on-going duct construction work and the problem appeared to vanish with the completion of this construction work. This would tend to imply that the source of the "dust problem" was the construction work on the HVAC duct system. This conclusion is reinforced by the results of the analysis of the "dust problem" air samples, presented above. The components identified in the air samples appeared to be derived from duct insulation or other forms of insulation.

Evaluation of the Third Step

If it is assumed that the month of May in Washington, DC is typically a wet and mild month, the data collected by the GSA during that month is in contradiction to those conditions. It shows virtually no influence of the outside atmospheric humidity on the interior air. This implies that there was very little intake of fresh outside air to the building's HVAC system. In fact, rough calculations tend to indicate that the outside air intakes were probably closed and that the only outside air entering the building was leakage through the intake dampers, as follows:

1. At a low external relative humidity (RH) of 25%, the recorded low interior RH of 12% and a 5% intake volume rate:

   95%(12%RH) + 5%(25%RH) = 12% interior RH.

2. At a nominal external relative humidity of 50%, the recorded nominal interior RH of 20% and a 5% intake volume rate:

   95%(20%RH) + 5%(50%RH) = 21% interior RH.

*ASHRAE Handbook of Fundamentals, Chapter 8-Physiological Principles, Comfort and Health, Figures 3A, 3B and 3C.

3. At a maximum external relative humidity of 100%, the recorded maximum interior RH of 40% and a 5% intake volume rate:

   95%(40%RH) + 5%(100%RH) = 43% interior RH.

Also, and as indicated earlier, there should have been a very low level heating requirement during this month. Consequently, drying of the outside air by heating should have had small effect in the resulting interior humidity. Thus, it appears that the intake of outside air had to be on the order of 3% to 5%, and was probably only leakage through closed air intakes.

QUESTIONS REGARDING THE COOKING ODOR COMPLAINTS

Since the cooking odor complaints were specific, and had received considerable attention, some questions immediately came to mind. They were as follows:

1. Was there any possibility of a source or sources of the cooking odors other than the first floor fast food restaurant?

2. What was the general distribution of the cooking odor complaints through the building?

3. What was the vertical distribution of the cooking odor complaints within the building?

In response to the first question, it was determined that the below grade parking levels of the building extended beneath restaurants that were not within the building. Thus, the first floor fast food restaurant was not the only possible source of cooking odors or cooked food odors.

In answer to the second and third questions, it was determined that all complaints were from work areas above the second floor of the building. It was further determined that absolutely no evidence of cooking odors existed on the first floor and the mezzanine level, and that only a few locations had complained of the problem. This information immediately indicated that the path of the cooking odor gases was not through the rooftop outside air intakes. If the main HVAC system had been intaking these gases, the odors would have been distributed through

a large part of the building, if not the total building. Consequently, the A&E firm's solution to the problem was clearly a guess at the cause of the cooking odor complaints.

QUESTIONS REGARDING THE COMPLAINTS IN GENERAL

In addition to the questions about the cooking odor complaints, it was necessary to ask two other significant questions. They were as follows:

1. What was the vertical distribution of all complaints received?

2. Were the complaints generated over the course of a full year in a fairly uniform manner or did they appear to be seasonally related?

The answer to the first of the above two questions was that all of the complaints were from work spaces above the second floor of the building. This was a very significant piece of information. There were six floors of the building above the second floor and the three below grade levels with the first floor, the mezzanine level and the second floor also formed a total of six levels.

The answer to the second of the above two questions was as significant as the answer to the first question. All of the complaints were generated during the cold winter months and the cool early months of spring.

ACTION

The initiation of the investigation of this problem was delayed by an earlier decision to await the completion of the construction work and the exhaust stack modification. This was done to avoid any possible transient effects of that work. Unfortunately, an extremely heavy work load at EPA headquarters caused some additional delay. About the middle of May, GSA's building manager evidenced concern over this delay. He was very concerned about the non-restaurant related odor complaints. The commencement of the investigation was then scheduled on an as-soon-as-possible basis, within committments to EPA.

INVESTIGATIVE ACTIVITY

The investigation commenced on 24 May 1984, after completion of the duct work and the stack extension installation. At that time there was no evidence that these measures had or had not corrected the indoor air problem(s) which had stimulated all of the complaints. There was also no evidence that the air problems still existed after these measures had been completed. However, the vertical location of all of the spaces or rooms occupied by the complainants, as illustrated in Figure 1, and the fact that the complaints were received during the cold or cool seasons, implied that the air "pollutants" were migrating vertically because of "stack effect", i.e., due to thermal buoyancy forces. The theoretical "stack effect" behavior for summer and winter in the USIA building are presented in Figures 2 and 3, respectively. The vertical migration hypothesis was further reinforced by the horizontal locations of the involved workspaces. Six of the ten complaints had been received from locations in the near vicinity of the elevator hoistways, stairwells and the shaft containing the exhaust stack for the fast food restaurant, as illustrated in Figure 4.

Funding Constraint

Very significant to the resolution of this indoor air pollution problem was the lack of funds to support its resolution and the lack of concern on the part of the building's owner. Consequently, it was necessary to develop an investigative approach that would have

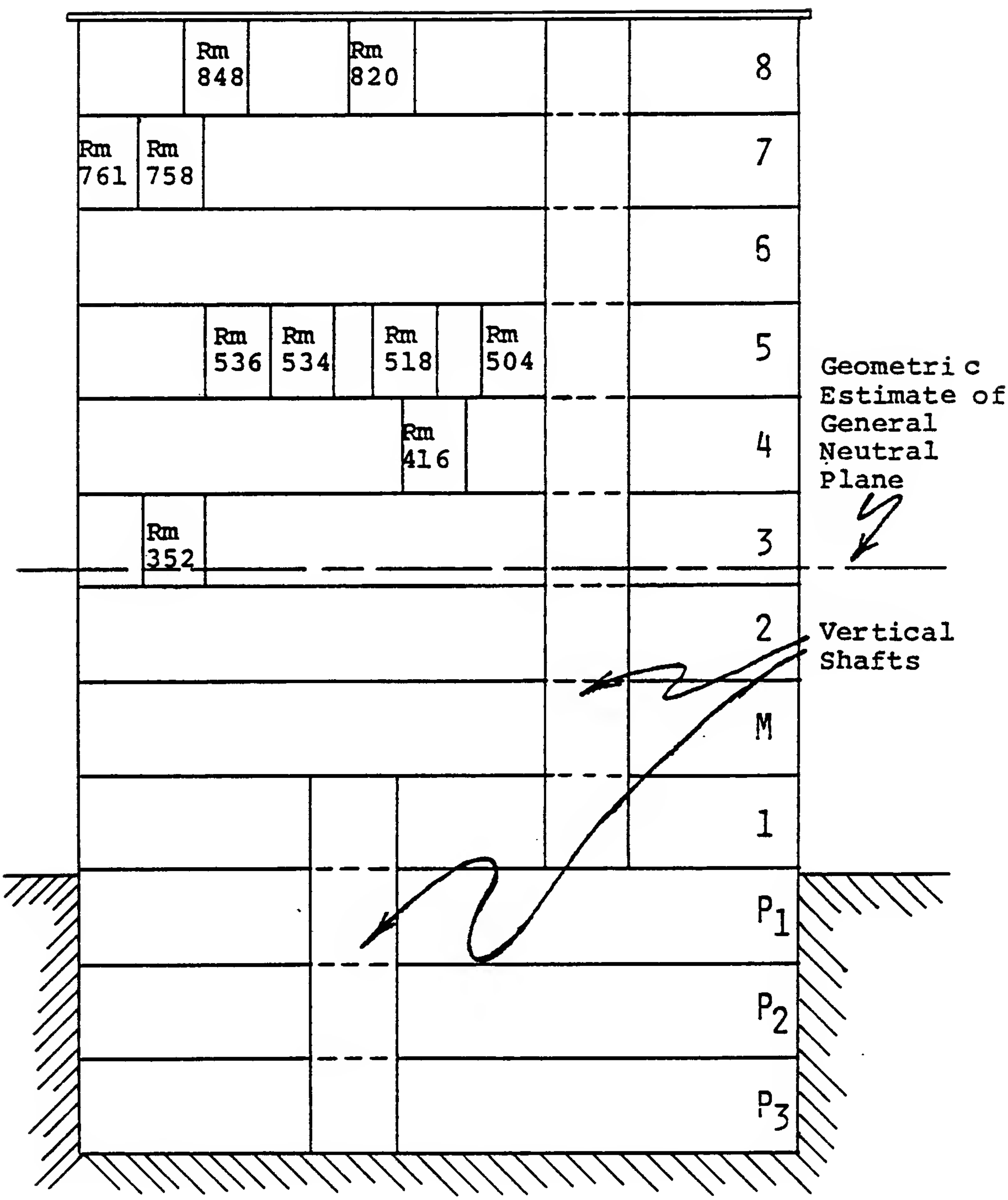

FIGURE 1. VERTICAL DISTRIBUTION OF COMPLAINT SPACES

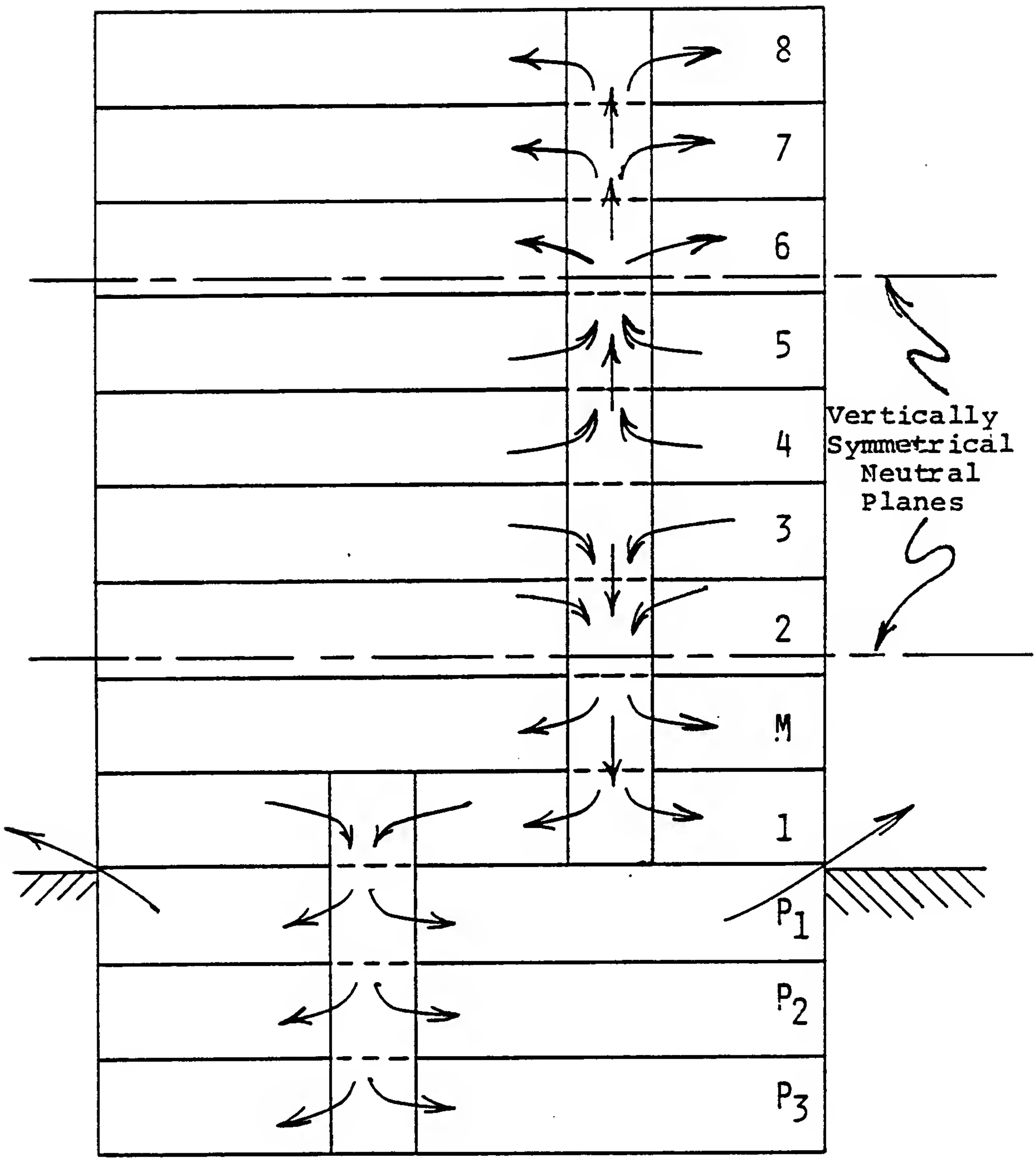

FIGURE 2. THEORETICAL SUMMER OR WARM SEASON VERTICAL AIR MIGRATION BEHAVIOR DUE TO THERMAL BUOYANCY

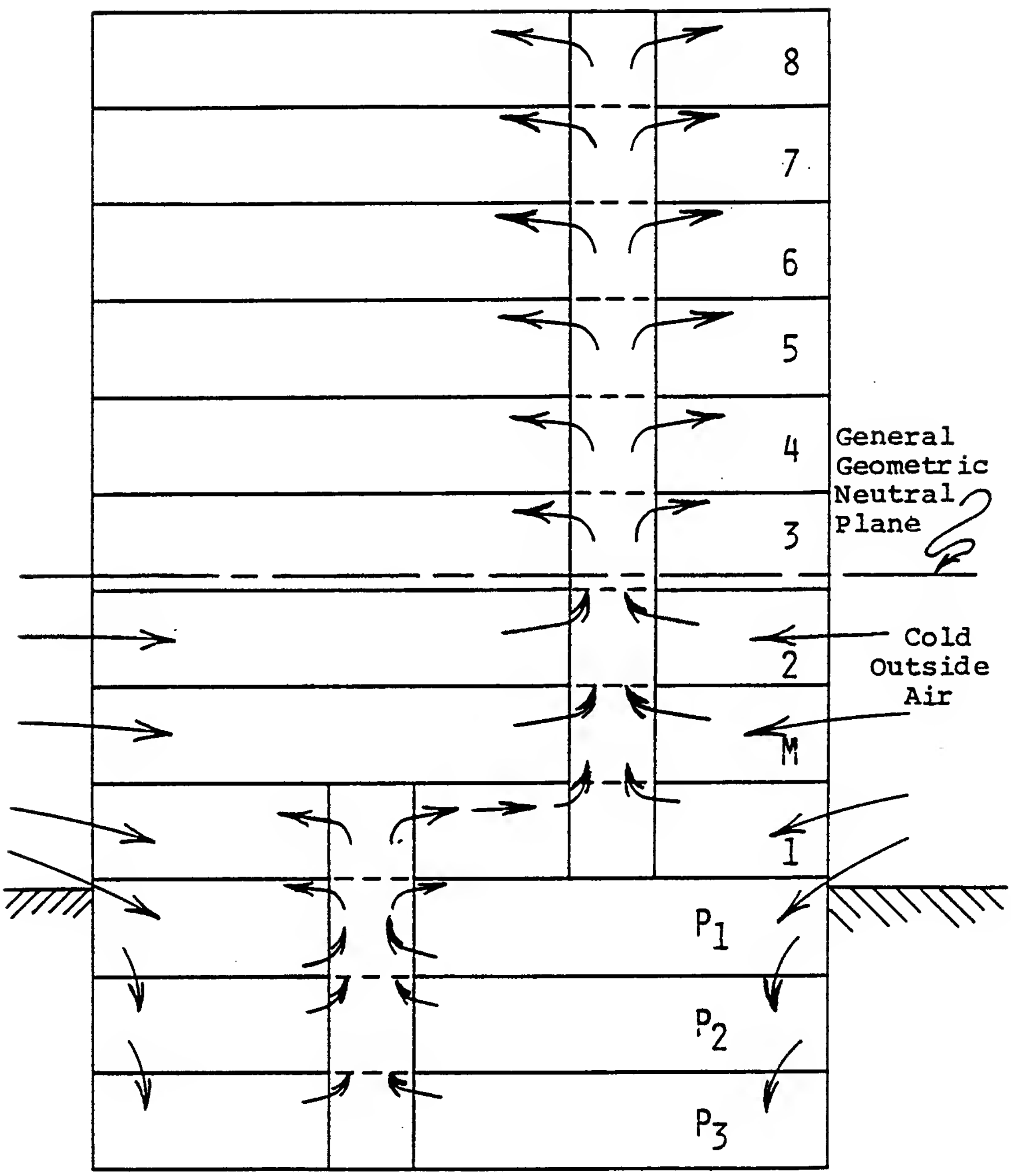

FIGURE 3. THEORETICAL WINTER OR COOL SEASON VERTICAL BEHAVIOR DUE TO THERMAL BUOYANCY

Complaint Spaces

1	Rm. 848	6	Rm. 518
2	Rm. 820	7	Rm. 416
3	Rm. 758	8	Rm. 352
4	Rm. 536	9	Rm. 534
5	Rm. 504	10	Rm. 761

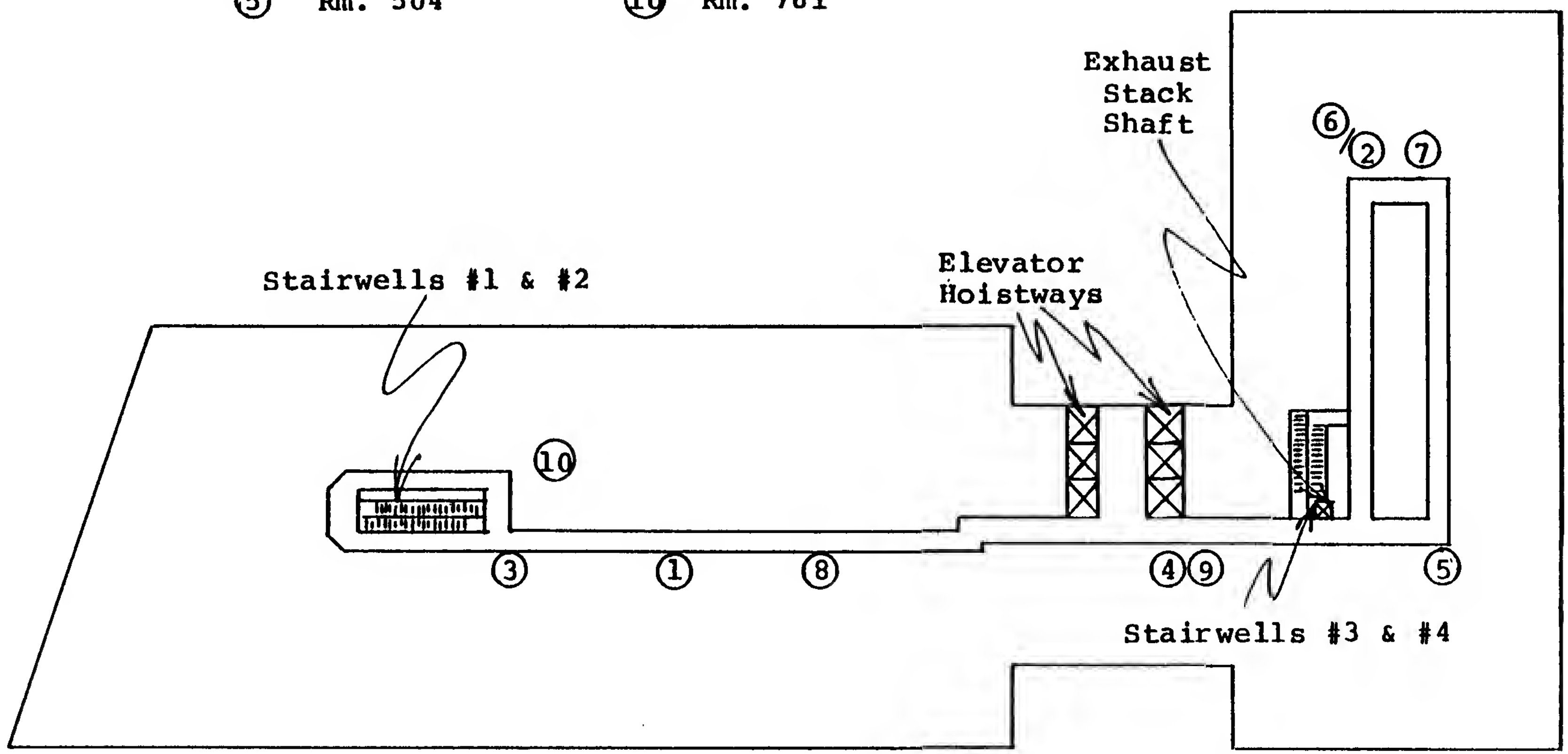

Figure 4. Horizontal Pattern of Complaint Spaces

virtually no cost. The approach developed was a minimal interior air behavior investigation. This approach would use less than ten mandays of effort, including the time contributed by USIA's Health and Safety Officer.

Investigative Approach

The plan for conducting the investigation was based upon determining the behavior of the interior air of the USIA building and, if possible, to identify the migrational paths of the pollutants from this behavior. However, there was also knowledge of a recently initiated EPA "Indoor Air Pollution Research Program", and there was a possibility of having the USIA building included in this research program, as a test site. If this could be accomplished, air samples would be acquired from the interior of the building and subjected to a rather thorough chemical analysis. Also, and very importantly, there would be no cost to the GSA for the acquisition of the air samples, the chemical analysis of the samples or the preparation of the report on the analysis. Consequently, the strategy that was suggested to the GSA's building manager was to conduct an essentially minimal migrational behavior investigation and to allow the USIA building to be used as a test site in EPA's on-going "Indoor Air Pollution" research program. He accepted this proposed approach. He was also informed that if the behavior data acquired were inconclusive, the more powerful approach of performing trace gas migration studies to determine the behavior of the building's interior air could be employed.

INTERIOR AIR BEHAVIOR INVESTIGATION

The proposed minimal air behavior investigation was predicated on determining the interior air movement characteristics of the building from pressure differential measurements, air velocity measurements, air temperature measurements, cross sectional areas of leakage paths, and visual observation throughout the interior of the building. The performance of this investigation required the following steps:

1. To become familiar with all aspects of the

building that could affect the behavior of the interior air environment.

2. To prepare a detailed plan for the measurement of the dynamic behavior of the building's interior air and existing state conditions.

3. To measure and record the dynamic behavior of the interior air and the state conditions existing at the time of the dynamic measurements.

4. To reduce and analyze all of the data and information collected.

5. To draw conclusions from the results of the analysis and prepare a report to the GSA on the results of the investigation.

The first requirement, as indicated above, was to become familiar with the building and its systems. The USIA's Health and Safety Officer provided a general description of the building. Copies of the architectural and mechanical drawings of the building were acquired and reviewed in detail. A meeting was held with the supervising stationary engineer, who was responsible for the maintenance and operation of the building's mechanical systems and equipments. All possible information related to these systems and equipments, including all vertical shafts and the relationship of the building's air intakes and exhaust stacks, was extracted from the stationary engineer at this meeting.

<u>Air Behavior Measurement Plan</u>

The air behavior measurements and other data to be collected were limited to the following factors:

1. Pressure differentials between building rooms, spaces, compartments, shafts, etc.

2. Positive pressure side identification across a pressure barrier to establish the direction of air flow.

3. Dimensions of air leakage channel cross sections,

i.e., exfiltration and infiltration paths.

4. Speed of air flow through leakage channels.

5. Temperature of the air on each side of a pressure barrier, in an air column, etc.

6. Recording other observed relevant factors.

Candidate Vertical Migration Paths - The review of the design and as-built state of the USIA building indicated that several possible vertical migration routes existed within the building. The major candidates were the south wing stairwells and elevator shafts. However, it was decided that all vertical routes should be considered and, thus, all accessible and possible leakage paths between these vertical routes and each floor level became candidate sampling points. They were as follows:

1. Above grade stairwells #1, #2, #3 and #4.

2. Below grade stairwells #5 and #6.

3. Above grade elevator shafts #1, #2, #3, #4, #5 and #6.

4. Below grade elevator shafts #7 and #8.

5. The communications cable shaft on the south side of the elevator shafts, above grade.

6. The fast food restaurant exhaust stack shaft on the north side of the elevator shafts.

There were, in addition,a number of utility service chases. However, these chases were reported as having their respective floor-deck penetrations and their shaft-wall penetrations tightly sealed with fire stopping. These potential vertical routes were also essentially inaccessible for the acquisition of air movement data.

Acquiring data on the above listed candidate vertical migration routes was limited to those where access was immediately available. This restricted measurements to the stairwells and elevator shafts, in general. Access to

the communications cable shaft was limited to the mezzanine level.

Measurement Instrumentation

The instrumentation necessary to acquire the above specified variables and parameters are listed as follows:

1. A manometer to measure pressure differentials.

2. An anemometer to measure air speeds.

3. A thermometer to measure air temperature.

4. A measuring tape to obtain the dimensions of air flow channels.

Manometer Requirements - Because moderate atmospheric temperatures existed at the time of the field investigation and because the building was only twelve levels in height, pressure differentials were expected to be small in magnitude. Consequently, a manometer was selected that had a range from 0.00 to 0.25 inches of water pressure. It had a measuring resolution of plus or minus 0.0025 inches of water pressure and was of the magnehelic type.

Anemometer/Thermometer Requirements - Since mantime was extremely limited, it was important to select instruments that would provide rapid measurements and outputs. The hot wire electronic types of anemometers and thermometers provide almost instantaneous air speed and temperature readings. Consequently, these were the types selected for use in this investigation.

Data Recording - All output from the instrumentation was obtained visually and recorded manually. Data acquisition sheets were prepared in advance and used during the field investigation.

Acquired Data for the Above Grade Stairwells

The data acquired that reflected the infiltration or exfiltration contribution and migrational air behavior of the above grade stairwells are presented in Table 1 of

Appendix A. The direction of flow, pressure differential and volume flow rate between each stairwell and its respective corridor, at the time of the field investigation, are presented in Figure 5.

The leakage flow behavior evidenced in the acquired data, as illustrated in Figure 5, comes very close to the theoretical behavior presented in Figure 2 for summer conditions. The data for above grade stairwells #2 and #4, which are shown in Figure 5, definitely reflect the flow behavior illustrated in Figure 2. The switching of flow direction in these stairwells appears to occur at the 5th floor level, with two neutral planes occurring. The upper neutral plane appears to occur in the vicinity of the 6th or 7th floors and the lower neutral plane appears to occur in the vicinity of the deck of the 2nd floor. Figure 5 also presents estimates of the volume flow rates, which were calculated from the acquired data using Equations 1 and 3 of Appendix B.

The theoretical behavior shown in Figure 2 assumes that everything is symmetrical, equivalent and balanced. However, these conditions do not exist in the USIA headquarters building and the results implied by the measured data reflect these differences. In general, other than the typical construction variations and lack of balancing in the HVAC system, there did not appear to be any large or significant cause for the migrational air flow through the stairwells in the USIA building to be different than that which should be expected.

Acquired Data for the Above Grade Elevator Shafts

The data acquired that reflected the infiltration or exfiltration contribution and migrational air behavior of the above grade elevator shafts are presented in Table 2 of Appendix A. The direction of flow, between the elevator shafts and the lobby on each floor, the pressure differentials and the estimated volume flow rate for each of these elevator shafts, at the time of the investigation, are presented in Figure 6. The estimated volume flow rates presented in Figure 6 were calculated using Equations 1 and 3 of Appendix B.

The leakage flow behavior of the above grade elevator

Adj. Hall	SW #1	Adj. Hall	SW #2	Adj. Hall	SW #3	Adj. Hall	SW #4	Floor
-.03	2340 CFM (Dr. open)	-.02	1755 CFM (Dr. open)	-.03		-.001		8
.005	6 CFM	.01	68 CFM	-.002	51 CFM	.02		7
.005	79 CFM	.000	46 CFM	.000	15 CFM	.02/.03	82 CFM	6
.02/.03	180 CFM	.025	124 CFM	.05	113 CFM	.03	124 CFM	5
.03	90 CFM	.01	90 CFM	.05	68 CFM	.02	113 CFM	4
.05	135 CFM	.04	98 CFM	.06	225 CFM	.02	113 CFM	3
.035	124 CFM	.02	60 CFM	.05	225 CFM	.02	135 CFM	2
.01	45 CFM	-.001	90 CFM			-.01	90 CFM	M
				.02	180 CFM	-.02	17 CFM	1

Notes: (1) Some stairwells are equipped with a ceiling return air/exhaust register.
(2) Pressure differentials are shown in inches of water pressure.

FIGURE 5. TOWER STAIRWELL - CORRIDOR LEAKAGE AIR FLOW

Lobby*	Elev. #1	Lobby*	Elev. #2	Lobby*	Elev. #3	Lobby*	Elev. #4	Lobby*	Elev. #5	Lobby*	Elev. #6	Floor
-.02	12.6 CFM ←	-.02	6.3 CFM ←	-.02	12.6 CFM ←	-.02	6.3 CFM ←	-.02	4.2 CFM ←	-.02	12.6 CFM ←	8**
.00	0.0 CFM ↔	.005	→	.00	0.0 CFM ↔	.00	0.0 CFM ↔	.00	0.0 CFM ↔	.003	→	7**
.00	94.5 CFM →	.00	94.5 CFM →	.00	52.5 CFM →	.00	94.5 CFM →	.00	42.0 CFM →	.00	84.0 CFM →	6
.01/ .02	109.2 CFM →	.01/ .02	111.3 CFM →	.01	107.1 CFM →	.01	140.7 CFM →	.01	105.0 CFM →	.015	126.0 CFM →	5
.00	21.0 CFM →	.00	73.5 CFM →	.005	63.0 CFM →	.005	52.5 CFM →	.005	73.5 CFM →	.005	54.6 CFM →	4
.02	111.3 CFM →	.01	73.5/ 147.0 CFM →	.02	113.4 CFM →	.02	126.0 CFM →	.02	107.1 CFM →	.015	107.1 CFM →	3
.02	96.6 CFM →	.02	73.5/ 147.0 CFM →	.02	73.5/ 128.1 CFM →	.015	23.5/ 107.1 CFM →	.015	75.6 CFM →	.015	107.1 CFM →	2
-.00	10.5 CFM ←	-.00	77.7 CFM ←	-.00	63.0 CFM ←	-.00	77.7 CFM ←	-.00	73.5 CFM ←	-.00	88.2 CFM ←	M
-.01	155.4 CFM ←	-.01	128.1 CFM ←	-.01	128.1 CFM ←	-.01	140.7 CFM ←	-.01	161.7 CFM ←	-.01	176.4 CFM ←	1

Notes: *Flow rates shown are only for the center crack between the elevator doors for the floors shown.
**Pressure differentials shown are in inches of water pressure.

FIGURE 6. TOWER ELEVATOR SHAFTS - LEAKAGE AIR FLOW BEHAVIOR

shafts, as illustrated in Figure 6, is very similar to that evidenced by the above grade stairwell data discussed in the previous section. Further, the elevator leakage flow behavior is almost identical to the theoretical or anticipated flow behavior shown in Figure 2, for summer conditions. In fact, the data generally imply that somewhere around the 4th floor level is where flow direction switching occurs in the elevator shafts and that two neutral planes exist in each shaft. The upper neutral plane appears to exist somewhere in the upper part of the seventh floor or the deck of the eighth floor. The lower neutral plane appears to exist in the upper part of the mezzanine or the deck of the second floor, as illustrated in Figures 6 and 7.

Migration via Utility Shafts/Chases/Spaces

In general, the restrooms, and utility and service spaces did not appear, from visual inspection and measured data, to provide a path to their related vertical chases and shafts that would allow the transport of buoyant pollutants to the floors occupied by the complainants. The data measured, as shown in Table 3 of Appendix A, indicate an almost totally positive pressure condition in all corridors adjacent to these spaces, with one exception. The only negative pressure differential measured was at the telephone closet on the north side of the 8th floor elevator lobby, and this pressure differential was very small. However, there were an additional ten (10) space-corridor locations with pressure differentials very near zero. The air flow at these locations could easily switch direction with small changes in either or both the internal and external atmospheric conditions. If the state conditions existing at the time of the field investigation were maintained through all seasons, infiltration of the floors occupied by the complainants via these routes is not possible, or at least it would not be significant.

The ability to transport buoyant pollutants via these routes is also strongly dependent upon the lack of sealing of the vertical and horizontal penetrations through fire separations, which is required by code. Such penetration sealings significantly inhibit the transport of buoyant pollutants through these leakage paths.

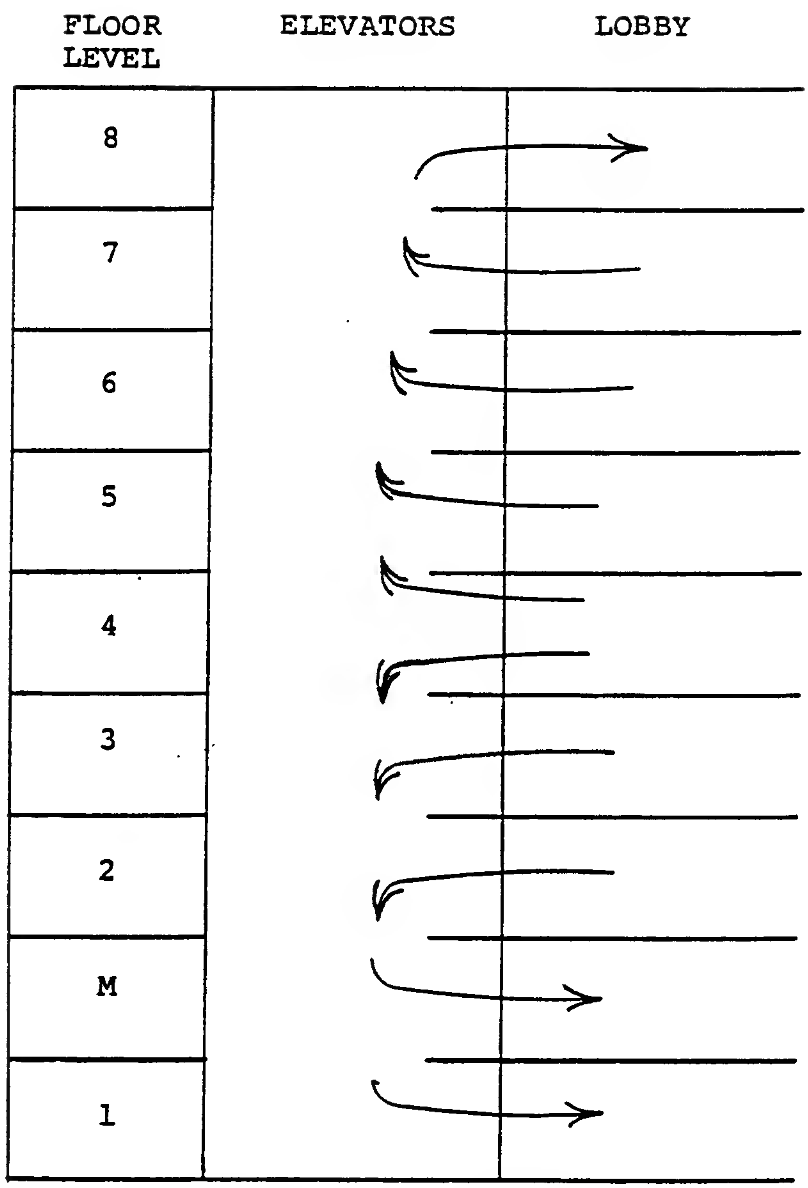

FIGURE 7. GENERALIZED AIR FLOW BEHAVIOR IN THE ABOVE GRADE ELEVATOR SHAFTS

In general, significant migration of buoyant pollutants via these routes within the USIA Headquarters building did not appear to be possible.

Migrational Air Flow Between Corridors and Complaint Sites

The data acquired between the spaces occupied by the complainants and their adjacent corridors are presented in Table 4 of Appendix A. The measured data clearly indicate why rooms 504 and 536 are subject to the infiltration of external buoyant pollutants. The air pressure in the corridor adjacent to these spaces was higher than the pressure in these spaces. Consequently, the flow of air was from the corridors to these rooms. The measured air velocity through the open corridor doors at approximately mid-height of the doorway was significant for both rooms. This indicated that a significant volume flow rate existed from the corridor into these rooms. This air flow rate was approximately 1200 CFM of corridor air flowing into room 504 and 4200 CFM of corridor air flowing into room 536, with the corridor doors open. These estimated volume flow rates assumed that the air velocity measured near the center of each open corridor doorway was the maximum velocity, and that it degraded to zero at the edges of the doorways in a linear fashion. Consequently, these estimated flow rates are conservative in magnitude. The pressure relationships found between these rooms and their adjacent corridors are improper. The occupant spaces should be at higher pressures than their respective adjacent corridors.

Additionally, the rates of flow from the air supply diffusers were measured in room 504 because of the additional complaint from this room regarding the general condition of the air in this room. The total air supply rate from the diffusers was estimated at 2.5 air changes per hour for room 504, which is a minimum air change rate for this type of workspace. It also assumes that a proper mix of outside air and recycled air exists in the supply air.

Rooms 848, 822, 518, 416 and 352 all had marginal pressure differentials with their respective adjacent corridors. A small change in HVAC system behavior, internal air

temperature, external air temperature, or the dynamic behavior of the external atmosphere, or any combination of these conditions could easily change these pressure differentials and the direction of air flow between these rooms and their corridors. Thus, winter conditions could easily induce a flow from the corridors into these rooms. This reversal of flow during the winter could also include room 758, which only had a positive pressure differential of .01 inches of water pressure.

Acquired Data for the Below Grade Elevator Shafts

The data measured relative to the migrational behavior of air through the below grade elevator shafts are presented in Table 5 of Appendix A. The data definitely confirm the flow behavior predicted for summer conditions in Figure 2. The direction of flows into and out of these shafts, as indicated by the measured data, are shown in Figure 8. The flow behavior is identical to that shown earlier in Figure 2.

Acquired Data for the Below Grade Stairwells

At the time the measurements were made, the below grade stairwells were essentially in balance with the below grade garage levels, i.e., there were only very small flow rates due to thermal buoyancy forces. The temperatures within the stairwells and the garage levels were essentially the same. Under such conditions there should be very little, if any, air migration and transport of buoyant pollutants via these stairwells.

However, the measurements taken did reflect the expected behavior for summer conditions which is illustrated in Figure 2. The actual data implied flow behavior and relevant data are presented in Figure 9.

Unbalanced Corridor Air Flow

A serious unbalanced condition was noted between the north and south HVAC systems. A high velocity air flow from the south wing into the elevator lobby and a correspondingly high velocity air flow from the elevator lobby into the north wing, via the connecting corridors, was observed and measured on several floors of the building. The measured

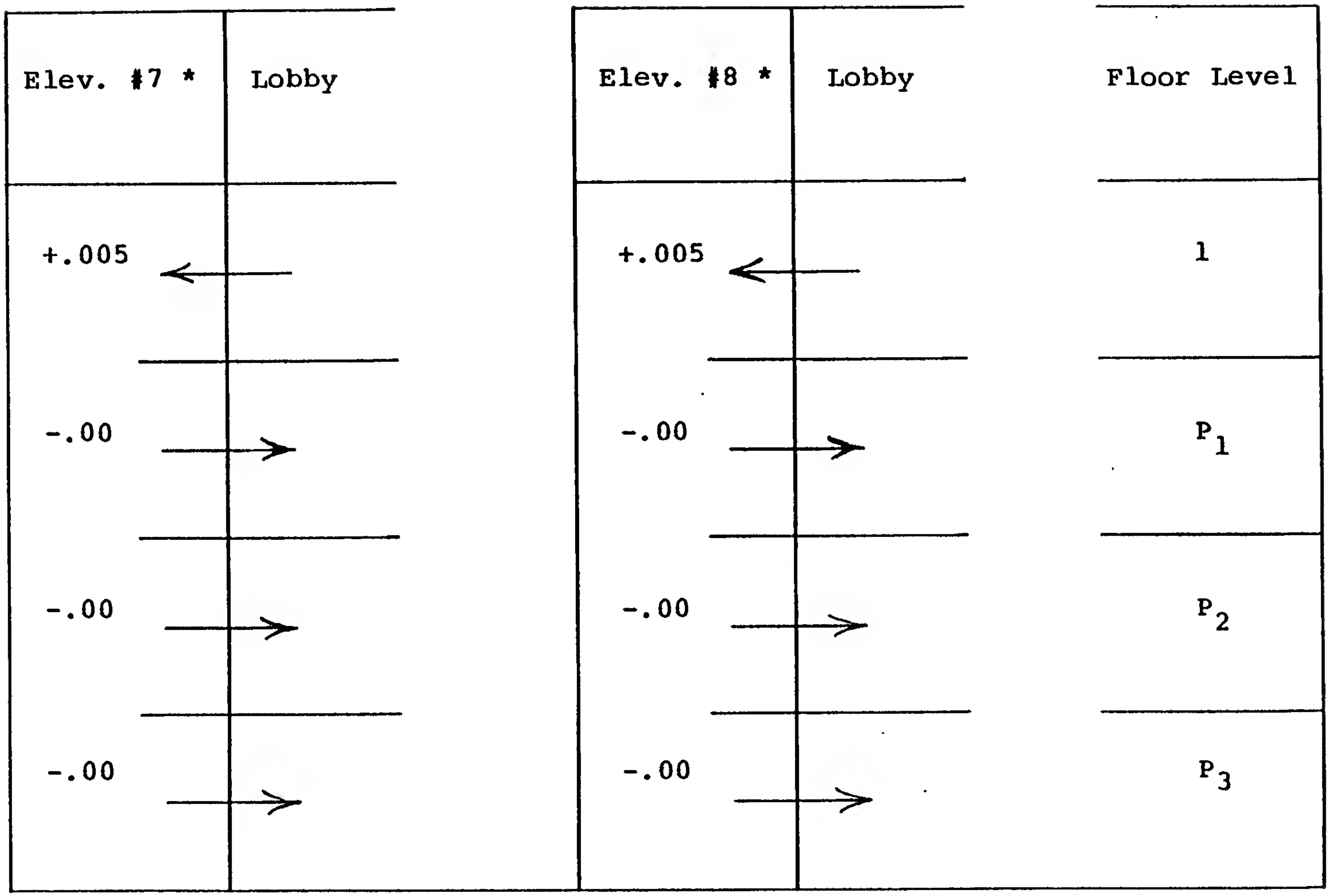

FIGURE 8. BELOW GRADE ELEVATOR SHAFTS - LEAKAGE FLOW BEHAVIOR

Note: *Pressure differentials are shown in inches of water pressure.

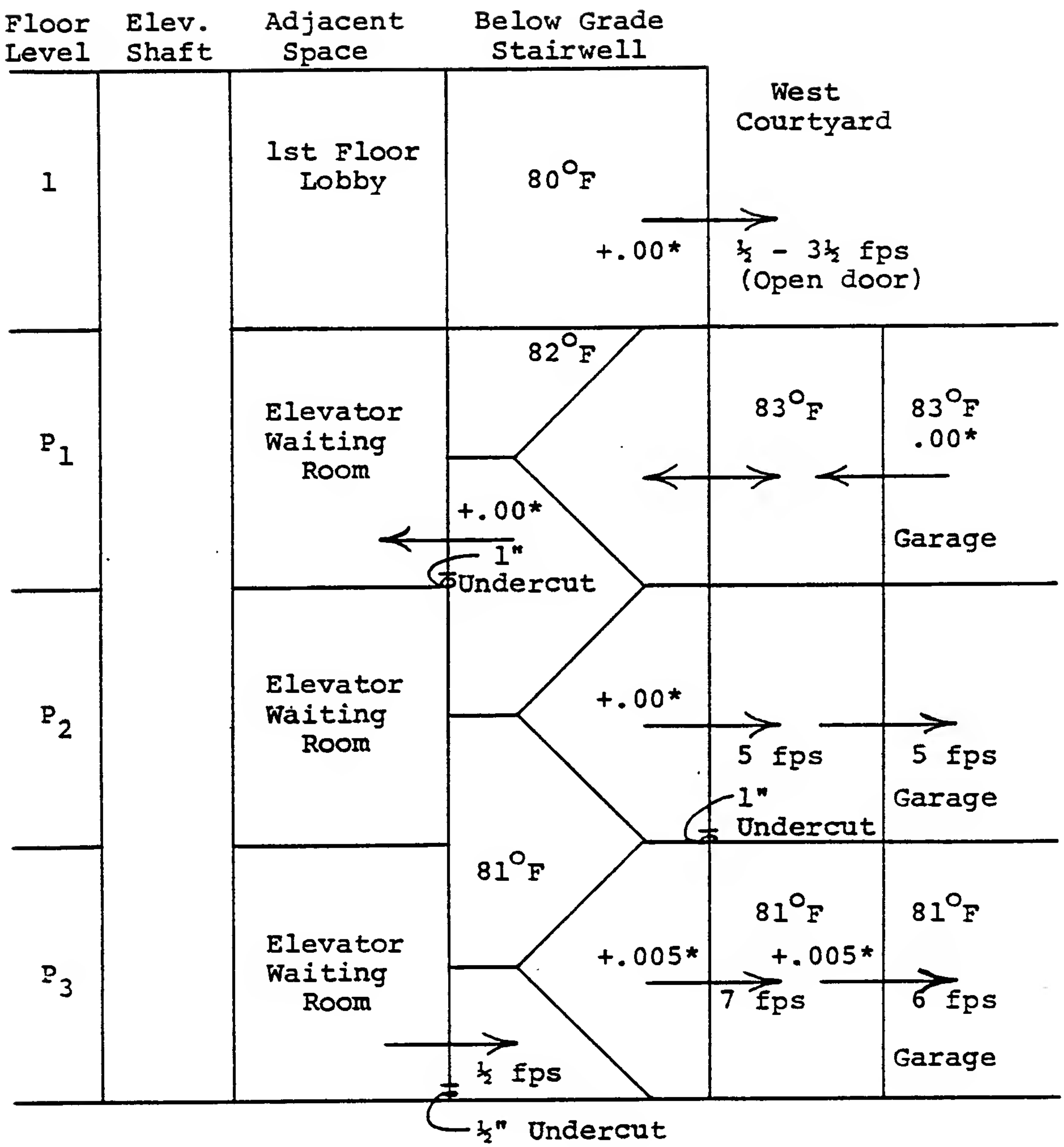

FIGURE 9. FLOW BEHAVIOR/DATA FOR BELOW GRADE WEST COURTYARD STAIRWELL

Note: *Pressure differentials are shown in inches of water pressure.

data are presented in Table 6 of Appendix A. To indicate the severity of this unbalanced condition, estimates of the volume flow rates of the air flowing through the corridor-lobby doors were calculated and are also presented in Table 6 of Appendix A. These volume flow rates range from 1800 CFM to 7200 CFM, depending upon the floor level and lobby door.

This condition fully explains the tendency of the spaces occupied by the complainants to primarily occur near the elevator lobby and in the north wing, as shown in Figure 4. This air stream provides the horizontal migrational mechanism for each of the upper floors.

The existence of this horizontal flow implies the need for the pollutant input location on each floor, i.e., the infiltration location(s), to be upstream of the involved spaces. Table 7 of Appendix A indicates the candidate vertical infiltration routes that would satisfy the vertical and horizontal location of each of the spaces occupied by complainants. The implication of Table 7 of Appendix A is that stairwells #1 and #2, and the communications cable shaft are the most likely vertical migration routes. The above grade elevator shafts are the second most likely vertical migration routes.

In general, this unbalanced condition of the north and south HVAC systems requires correction. It must be corrected before any attempt is made to stabilize pressure relationships between occupant spaces and adjacent corridors.

<u>Other Measurements</u>

A number of other measurements were made at locations which could possibly provide insight into the nature of the migrational behavior of the interior air of the USIA building. Those that provided significant information are discussed in the following material.

<u>Communication Cable Shaft</u> - The door leakage characteristics to the access room for the communications cable shaft on the mezzanine level were measured, with the following results:

1. A pressure differential of .05 inches of water pressure was measured across this door, with the shaft at a lower pressure than the mezzanine corridor.

2. The door had a one inch undercut, with a resultant 1/4 square foot cross sectional air leakage area.

3. An air velocity of 13 fps through the undercut from the corridor to the shaft was measured.

These data indicate that a volume flow rate of approximately 200 CFM was entering the shaft at the time of the field investigation. This flow would be higher under winter conditions. Also, and very importantly, any flow entering this shaft must exit this shaft either by a vent and/or leakage to the upper floors and/or outside atmosphere.

Mezzanine Door at Rear of North Elevator Bank - Measurements were taken at the undercut of the door at the rear of the north bank of elevators on the mezzanine level. The space behind this door was later determined to be another mechanical room. The acquired data were as follows:

1. A pressure differential of .02 inches of water pressure was measured at the undercut of the door, with the corridor air at the higher pressure.

2. The door had a 1.25 inch undercut, with a resultant leakage flow area of .31 square feet.

3. The corridor temperature was $79^{\circ}F$.

4. An air velocity of 9 fps was measured through the undercut.

These data indicate a volume flow rate of approximately 170 CFM of air entering the mechanical room from the corridor, with the door closed.

Loading Dock/Garbage Dumpster Area - Measurements were taken at the double doors between the first floor corridor and the loading dock area, which also contained the garbage

dumpster for the fast food restaurant. At the time of the investigation, the external overhead doors to 4th street were open. The data measured were as follows:

1. An air velocity of 2 fps was measured through the 3' by 6'6" door between the corridor and the loading dock area.

2. The corridor temperature was 78^{o}F.

3. The loading dock temperature was 82^{o}F.

4. The interior corridor pressure was higher than the loading dock area pressure. The air flow was from the corridor to the loading dock area, which was expected.

5. The doors had a one inch undercut.

The volume flow rate through the door at the time of the measurements was approximately 1200 CFM. Under winter conditions, the flow direction would reverse and the volume flow rate would be a function of the difference between the exterior atmospheric temperature and the interior building temperature, without wind effect.

Fast Food Restaurant Lobby Entrance - Measurements across the lobby entrance to the fast food restaurant were as follows:

1. There was no significant pressure differential across the interior entrance doorway, with the doors closed. However, the lobby was at a higher air pressure than the restaurant, at the time.

2. The restaurant temperature was 74^{o}F.

3. The lobby temperature was 73^{o}F.

Other Locations - Several other potential air migration locations were measured but no significant data or insightful information were acquired.

APPENDIX A

MEASURED INTERIOR AIR BEHAVIOR DATA

for the

USIA HEADQUARTERS BUILDING

TABLE A-1. ABOVE GRADE STAIRWELL DATA

STAIRWELL #1

Floor Level	SW Temp. (°F)	Corridor Temp. (°F)	Pressure* Diff. (In. H_2O)	Air Flow (fps)	Flow Area (ft^2)
8	82	79	-.03	2**	19.5
7	81	79	+.005	5	.188
6	81	78	+.005	7	.188
5	79	77.5	+.02/.03	12	.25
4	80	79	+.03	12	.125
3	79	77	+.05	12	.188
2	78	77.5	+.035	11	.188
M	80	79	+.01	6	.125
1	--	--	----	--	----

* Positive sign implies overpressure in corridor.

** Door was open.

TABLE A-1. ABOVE GRADE STAIRWELL DATA (CONT.)

STAIRWELL #2

Floor Level	SW Temp. (^{o}F)	Corridor Temp. (^{o}F)	Pressure* Diff. (In. H_2O)	Air Flow (fps)	Flow Area (ft^2)
8	80	78	-.02	1.5**	19.5
7	79	77	+.01	6	.188
6	79	78	+.00	3.5	.22
5	79	78	+.025	11	.188
4	81	79	+.01	8	.188
3	78	75	+.04	13	.125
2	78	78	+.02	8	.125
M	80	79	-.001	6	.25
1	--	--	----	--	----

* Positive sign implies overpressure in corridor.

** Door was open.

TABLE A-1. ABOVE GRADE STAIRWELL DATA (CONT.)

STAIRWELL #3

Floor Level	SW Temp. (°F)	Corridor Temp. (°F)	Pressure* Diff. (In. H_2O)	Air Flow (fps)	Flow Area (ft^2)
8	75	--	-.03	6**	19.5
7	76	--	-.002	4.5	.188
6	76	76	.00	2	.125
5	77	76.5	+.05	10	.188
4	78	78	+.05	7/11	.125
3	78	--	+.06	15	.25
2	80	77	+.05	15	.25
M	--	--	----	--	----
1	--	73	+.02	8	.375

* Positive sign implies overpressure in corridor.

** Door was open.

TABLE A-1. ABOVE GRADE STAIRWELL DATA (CONT.)

STAIRWELL #4

Floor Level	SW Temp. (°F)	Corridor Temp. (°F)	Pressure* Diff. (In. H_2O)	Air Flow (fps)	Flow Area (ft^2)
8	77	78	-.001	--	.25
7	78	77	+.02	--	.22
6	78	75	+.02/.03	11	.125
5	78	78	+.03	11	.188
4	77	77	+.02	10	.188
3	75	74	+.02	10	.188
2	76	76	+.02	9	.25
M	77	80	-.01	6	.25
1	78	--	-.02	4	.07

* Positive sign implies overpressure in corridor.

TABLE A-2. ABOVE GRADE ELEVATOR DATA (CONT.)

				Elevator #1			Elevator #2		
Floor Level	Lobby Temp. (°F)	Flow Area* Doors Center	Flow Area* Doors Sides	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)
8	80	.07	.35	-.02	3	--	-.02	1.5	--
7	77	.07	.35	.00	0.0	--	+.005	0.0	--
6	78	.07	.35	.00	0.0	4.5	.00	0.0	4.5
5	76	.07	.35	+.01/.02	1	5	+.01/.02	1.5	5
4	77	.07	.35	+.00	0.0	1	+.00	0	3.5
3	75	.07	.35	+.02	1.5	5	+.01	0	3.5/7
2	76	.07	.35	+.02	0.5	4.5	+.02	0	3.5/7
M	79	.07	.35	-.00	0.5	4	-.00	1	3.5
1	78	.07	.35	-.01	2	7	-.01	0.5	6

* Flow area is in ft^2.
** Positive sign indicates overpressure in lobby.

TABLE A-2. ABOVE GRADE ELEVATOR DATA (CONT.)

				Elevator #3			Elevator #4		
Floor Level	Lobby Temp. (^oF)	Flow Area* Doors Center	Flow Area* Doors Sides	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)
8	80	.07	.35	-.02	3	--	-.02	1.5	--
7	77	.07	.35	.00	0	--	+.00	0	--
6	78	.07	.35	.00	0	2.5	.00	0	4.5
5	76	.07	.35	+.01	0.5	5	+.02	1	6.5
4	77	.07	.35	+.005	0	3	+.005	0	2.5
3	75	.07	.35	+.02	2	5	+.02	0	6
2	76	.07	.35	+.02	0.5	3.5/6	+.01	0.5	1.0/5
M	79	.07	.35	-.00	0	3	-.005	1	3.5
1	78	.07	.35	-.01	0.5	6	-.01	3.5	6

* Flow area is in ft^2.
** Positive sign indicates overpressure in lobby.

TABLE A-2. ABOVE GRADE ELEVATOR DATA (CONT.)

				Elevator #5			Elevator #6		
Floor Level	Lobby Temp. (^oF)	Flow Area* Doors Center	Flow Area* Doors Sides	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)	Pressure** Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)
8	80	.07	.35	-.02	1	--	-.02	3	--
7	77	.07	.35	.00	0	--	+.003	0	--
6	78	.07	.35	.00	0	2	.00	0	4
5	76	.07	.35	+.01	0	5	+.015	0	6
4	77	.07	.35	+.005	0	3.5	+.005	0.5	2.5
3	75	.07	.35	+.02	0.5	5	+.015	0.5	5
2	76	.07	.35	+.015	0.5	3.5	+.015	0.5	5
M	79	.07	.35	.00	0	3.5	.00	1	4
1	78	.07	.35	-.01	3.5	7	-.01	2	8

* Flow area is in ft^2.
** Positive sign indicates overpressure in lobby.

TABLE A-3. PRESSURE DIFFERENTIALS* BETWEEN UTILITY/ SERVICE SPACES AND CORRIDORS

Floor Level	South Wing		South Of Elevator Lobby				North of Elevator Lobby				
	Men's Rm	Wmn's Rm	Men's Rm	Wmn's Rm	Elect. Closet	Janitor Closet	Men's Rm	Wmn's Rm	Elect. Closet	Janitor Closet	Tele. Closet
8	+.02	+.05	+.08	+.01	+.01**	+.035	+.05	+.05	+.005	+.18	-.00
7	+.03	+.02	+.035	+.015	+.01	+.05	+.03	+.07	+.00	+.01	+.00
6	+.05	+.03	+.08	+.01	+.00	+.07	+.015	+.02	+.01	+.015	+.00
5	+.03	+.06	+.04	+.07	+.02	+.075	+.05	+.01	+.005	+.02	
4	+.045	+.04	+.01	+.04	+.00	+.04	+.06	+.10	+.015	+.04	+.00
3	+.03	+.04	+.005	+.04	+.01	+.04	+.05	+.02	+.01	+.01	+.01
2	+.03	+.035	+.06	+.015	+.02	+.05	+.06	+.05	+.02	+.01	+.00
M	---	---	---	---	---	---	+.02	+.02	---	---	---
1	---	---	---	---	---	---	---	---	---	---	---

* Pressure differentials are in inches of water pressure and a positive sign indicates the overpressure exists in the corridor.

** Ceiling tile missing above door.

TABLE A-4. WORKPLACE-CORRIDOR DATA

Floor Level	Room No.	Space Temp. (°F)	Pressure* Diff. (In. H_2O)	Air Flow (fps)
8	848	76	+.00	1
	822	76	+.00	2.5
7	758	76	+.01	2
5	518	75	+.005	2
	504	76	-.07	2**
	536	76	-.01	7**
4	416	76	+.00	0.5**
3	352	73	+.00	3**

* Positive sign indicates the overpressure is in the indicated workplace.

** Air speed measured with corridor-workplace door open.

TABLE A-5. BELOW GRADE ELEVATOR DATA

Floor Level	Elevator #7				Elevator #8			
	Pressure* Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)	Elevator Shaft Temp. (^oF)	Pressure* Diff. (In. H_2O)	Air Flow Center (fps)	Air Flow Sides (fps)	Elevator Shaft Temp. (^oF)
1	+.005	0.5	3	80	+.005	1	3.5	80
P_1	-.00	0	0	80	-.00	0	0	80
P_2	-.00	1	4	80	-.00	1	4.5	80
P_3	-.00	0	0.5	80	-.00	0	0.5	80

* Positive sign indicates the overpressure to be external to the elevator shaft.

TABLE A-6. AIR FLOW FROM THE SOUTH WING TO THE NORTH WING
(UNBALANCED HVAC SYSTEMS)

Floor Level	South Corridor Pressure* Diff. (In. H_2O)	South Corridor Air Flow (fps)	South Corridor Volume Rate Estimate (CFM)	South Corridor Temp. (^{o}F)	Elev. Lobby Temp. (^{o}F)	North Corridor Pressure** Diff. (In. H_2O)	North Corridor Air Flow (fps)	North Corridor Volume Rate Estimate (CFM)	North Corridor Temp. (^{o}F)
7	+.06	5	6000	75	76	+.04	--	6000	78
6	+.04	3	3600	--	78	+.00	2	2400	--
5	+.07	6	7200	74	76	+.00	3	3600	74
4	+.04	5	6000	--	77	+.00	5	6000	--
3	+.115	6	7200	74	75	+.01	2.5/7	5400	75
2	+.04	4	4800	76	76	+.015/.02	3	3600	76
M	+.05	2.5	3000	78	79	+.01	1.5	1800	79

* Positive sign indicates an overpressure in the south corridor to the elevator lobby.

** Positive sign indicates an overpressure in the elevator lobby to the north corridor.

Note: Air flows were measured with the corridor-lobby doors open.

TABLE A-7. CANDIDATE ABOVE GRADE INFILTRATION ROUTES

		Vertical Infiltration Routes					
Floor Level	Complaint Space	Stair-well #1	Stair-well #1	Elevator Shafts	Stair-well #3	Stair-well #4	Communication Cable Shaft
3	352	X	X				X
4	416	X	X	X	X	X	X
5	504	X	X	X	X	X	X
	518	X	X	X	X	X	X
	534	X	X	X			X
	536	X	X	X			X
7	758	X	X				X
8	820	X	X	X	X	X	X
	848	X	X				X

APPENDIX B

INDOOR AIR POLLUTION

and

BUILDING LEAKAGE

INDOOR AIR POLLUTION AND BUILDING LEAKAGE

There are basically two approaches available to eliminate the existence of indoor air pollution problems. The first is the direct approach of eliminating the source of the air pollutants. The second is to utilize air engineering methods to prevent the presence or adequately reduce the concentrations of any undesirable air constituents.

POLLUTION SOURCE ELIMINATION APPROACH

The elimination of air pollutant sources, if accomplished responsibly, is a non-trivial process and requires a significant effort. In general, it requires the accomplishment of the following steps:

1. The identification of all significant pollutants within an indoor air system.

2. The identification of the source of each identified pollutant.

3. The determination of a method of treatment of each source.

4. The treatment of each identified source to prevent the generation and/or escape of the pollutants.

To accomplish the above steps requires substantial resources in funding, technical capability and equipments. These resources must be capable of accomplishing:

1. The development of an adequate air sampling plan that is unique to each potential air pollution case.

2. The performance of an adequate air sampling or monitoring of the problem facility.

3. The performance of a sophisticated chemical analysis of the collected air samples.

4. The performance of a thorough investigation of all potential sources of the air pollutants identified in the chemical analysis.

5. The specification of the measures necessary to inhibit the propagation of the pollutants at each identified source.

6. The modification of capital assets.

This is the approach classically followed by the Environmental Protection Agency (EPA) and chemically oriented investigators. The use of this approach is tedious, probably long term, difficult to accomplish and very costly if performed in a comprehensive and responsible manner. The effectiveness of this approach is completely dependent upon the adequacy of the sampling procedure, under all air systems variations, and the chemical analysis of the air samples, i.e., the extent of exhaustively identifying the set of all significant pollutants.

AIR ENGINEERING APPROACH

The air engineering approach is a preventive approach. It basically assumes that there may always be a possibility of air pollutants to contaminate an indoor air atmosphere. This approach is evidenced in the design handbooks of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), and a practicing air engineer should exert all possible effort to provide air system designs that inherently protect occupants from air pollutants. This would be for both new construction designs and modification construction designs.

This approach requires the use of all measures necessary to maintain absolute control of interior air environments. In existing construction, these measures may include:

1. HVAC system modifications and adjustments.

2. Installation of additional ventilation and/or exhaust fans to achieve:

    a. Flow control.

    b. Desired pressure relationships.

    c. Dilution of potential pollutants.

    d. Exhaustion of potential pollutants.

3. Sealing of enclosures within a facility.

4. Sealing of the external envelope of a facility.

In new construction, an air engineer should analyze the behavior of air throughout the interior of the facility being designed. During the design effort, all forces that may affect interior air behavior and all potential and realistic leakage paths must be considered and evaluated under worst case state conditions.

In addition to comfort conditions, air system design objectives for new and existing construction should include the prevention or adequate inhibition of the infiltration, migration, distribution and recirculation of air pollutants regardless of their nature or source.

System Degradation Considerations

Additionally, maintenance of air systems in existing construction often leaves much to be desired. It is often of an absolute minimum level and air systems are frequently out-of-balance to a substantial extent in existing construction. Compounding the degradation effects induced by minimum maintenance practices, additional reduction in system performance is induced by minimum operating policies and practices imposed by building owners to save energy and reduce costs. Consequently, an air system engineer should not only design to satisfy minimum code requirements and the practical needs of a facility but should also consider potential contamination by air pollutants induced by system performance degradation due to minimal maintenance and operation.

Practical Aspects

If a facility or building owner is to bear the cost of providing a clean indoor air environment, in an existing structure within a minimum time frame and at a minimum cost, the second approach is the most direct, most quickly implementable and probably the most cost effective. In general, even if pollutants are identified, a building owner should institute measures that would protect occupants while appropriate long term steps are taken to prevent the migration of such pollutants from their source or sources, or the elimination of the source or sources. The second approach is also probably the most effective means of providing short term protective measures for occupants while the first approach is being pursued.

Significant Contributing Factors

In dealing with indoor air pollution problems, it is extremely important to realize that the interior air movement of a building, particularly a high-rise building, is not totally a function of the HVAC system nor is its behavior seasonally constant. There are two significant forces, thermal buoyancy and dynamic wind forces, that cause air to move within a building and to move through its exterior envelope. The magnitude of such air movement, i.e., volume rates, within a building is directly dependent upon the as-built state and the maintained condition of the building. Factors that relate to these conditions include the number and size of cracks in the external envelope, the width of cracks around elevator doors, the width of undercuts in stairwell doors, the lack of sealing of floor and wall penetrations, and other factors that may be unique to a given building. Poor workmanship, poor inspection and cheap materials are typical causes of undesirable leakage conditions. When these conditions are coupled with significant thermal buoyancy forces and/or significant dynamic wind forces, the result can produce large concentrations of unknown air components within the interior environment of a facility. Combined, such leakage conditions form infiltration and migration paths within a structure. They can be difficult to identify and of an almost insidious nature. However, there are preventive measures that can be implemented to eliminate and/or minimize such paths and/or their effect within a facility.

"Stack Effect"

For the purpose of clarification, thermal buoyancy forces induce "stack effect", which directly causes vertical migration of fluids, but it can also significantly contribute to horizontal movement within a complex structure, such as a multiple occupancy high-rise building.

Given two adjacent columns of a fluid, compressible or incompressible, with significantly different temperatures and horizontal channels between such columns, thermally induced pressure differentials will exist that cause flow from one column to the other, as long as the temperature differences remain. The lower section of the cooler column will flow into the warmer column, and the upper section of the warmer column will flow into the cooler column, as illustrated in Figure B-1. The pressure

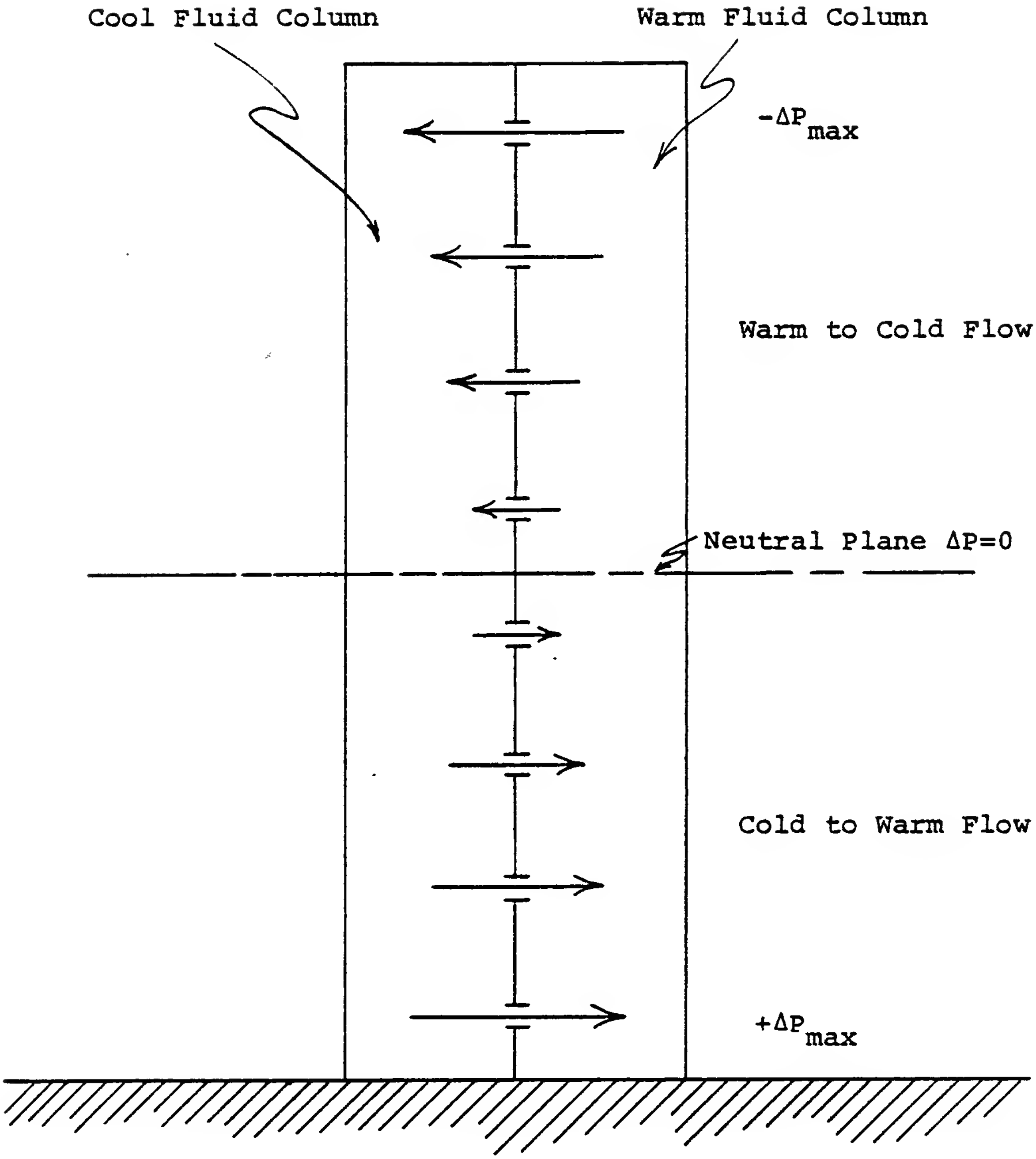

FIGURE B-1. "STACK EFFECT" FLOW BETWEEN FLUID COLUMNS
AT DIFFERENT TEMPERATURES

differentials are maximum, equal and opposite at the extreme ends of the columns, if the geometry of the columns is symmetric. If the columns and the connecting channels are vertically symmetric, the pressure differential at the mid-height of the columns will be zero. This point is usually referred to as the neutral plane because all points in a plane passing through both columns at this point are at the same pressure. If the columns are not vertically symmetric, the neutral plane will exist at a point unique to the column pair and away from the mid-height position of the columns.

This effect potentially exists between all connected pairs of air columns with different temperature profiles. Within a building, this effect potentially exists between:

1. The general interior air volume of a building and each vertical shaft within the building.

2. The general interior air volume of a building and the external atmosphere.

3. Each vertical shaft within a building and the external atmosphere.

4. Each pair of connected vertical shafts within a building, except when the temperatures within any such connected pair of shafts are identical vertically.

It is important to again point out that the location of the neutral planes of each possible pair of air columns within a facility will be unique to each particular pair of air columns. Further, the position of the neutral planes may vary in height seasonally.

Calculational Tools Available

A few well established relationships provide a readily available means to calculate estimates of the important variables that characterize a building's interior air behavior. These relationships are presented below.

Equation 1:

If the pressure differential and the cross sectional area of a horizontal channel connecting two air columns are known, as typified in Figure B-1, the mass

flow rate can be estimated, with some head loss, from an equation derived directly from Bernoulli's* steady state equation, as follows:

$F(lb/sec) = kA \quad 2g\rho\Delta P$, where:

- A is the effective channel cross sectional area (ft^2).
- k is the flow coefficient, ranging from 0.6 to 1.0.
- ρ is the density of the air on the inlet side of the horizontal channel (lb/ft^3).
- g is the gravitational constant (ft/sec^2).
- ΔP is the pressure differential between the air columns (lb/ft^2).

For moderate sized openings or channels, such as undercuts of stairwell doors, around elevator doors, etc., the contraction coefficient and approach factor are combined into the single coefficient k, i.e., as a function of geometry and Reynold's number. In such sized openings, the coefficient k ranges between 0.2 and 0.3.

<u>Equation 2</u>:

For very small openings and cracks, such as cracks around external windows, lintels, etc., the mass flow rate may be estimated from the following equation:

$F(lb/sec) = C(\Delta P)^n$, where:

- n is the flow exponent between 0.5 and 1.0.
- C is the flow coefficient.
- ΔP is the pressure differential between the air columns (lb/ft^2).

*ASHRAE Handbook of Fundamentals, Chapter 4 - Fluid Flow.

If the flow through such passages obeys Darcy's law, $n = 1$ in the above expression.

Equation 3:

The mass flow rate, F(lb/min), is quickly converted to a volume rate, as follows:

$Q(\text{SCFM}) = F(\text{lb/min})/\rho_s$, where:

ρ_s is the density of air under standard conditions (lb/ft^3).

SCFM is standard cubic feet per minute.

Equation 4:

To estimate the pressure difference, ΔP(Inches of water), due to "stack effect", at any given height, H, between two air columns, the following equation may be used:

$$\Delta P(\text{Inches of water}) = 7.64(1/(459.58 + T_c) - 1/(459.58 + T_h))\ (H - H_{np}),$$ where:

T_h = The temperature of the warmest air column (°F).

T_c = The temperature of the coolest air column (°F).

H = The height from a given reference height to the point where the pressure difference is to be estimated (ft).

H_{np} = The height from the same reference height used for H to the neutral plane of the two air columns (ft).

EPA INDOOR AIR POLLUTION PROJECT ACTIONS

EPA's Project Manager for its indoor air pollution research project approved the inclusion of the USIA building as one of the field test sites for the project. EPA's contractor, to perform this project, was directed to include the USIA building in the project at a meeting on 18 July 1984. This meeting was attended by EPA's Project Manager, contractor personnel and persons involved in the USIA building air pollution problem.

Air Pollutant Sampling Plan for the USIA Building

An air sampling plan was prepared by the contractor's project leader on 19 July 1984 and submitted to the USIA. The proposed air sampling, or monitoring, was planned to be performed between 1 August 1984 and 4 August 1984. Four sampling locations were specified in the plan, as follows:

1. The 8th floor near the elevator.
2. The 5th floor just outside the ladies restroom.
3. The 5th floor just outside of room 518.
4. The roof by the north air intake to the HVAC system.

Air samples were planned to be acquired twice daily, in the morning at approximately 7:00 AM and in the evening at approximately 7:00 PM. The air was to be collected by an air pump which would deliver the air to several sampling devices.

Project Specified Target Pollutants

The research project specification required that the contractor search for the existence of a certain set of air pollutant groups, with specific pollutants identified within each group. As a result, the sampling and analysis methodologies used in the performance of the project were well defined. The pollutants, pollutant groups, and the sampling and analytic methodologies specified for the project are presented in Table 1 of Appendix C.

Conduct of Air Sampling

The sampling, or monitoring, of the USIA building's interior air environment was conducted as planned and as specified in Table 1 of Appendix C.

Analytic Results From the Acquired Air Samples

The results of the chemical analysis of the air samples and the concentrations of the target pollutants found in the air samples were not received by the USIA until 1 May 1985. The results of the analysis were, when finally provided by the contractor, in a raw data form. These data required reduction and interpretation in order to be of any value. These raw data were sent to EPA Headquarters by the USIA Health and Safety Officer requesting that the necessary reduction and interpretation be performed so that the results and implications could be understood and used.

The results of this reduction and interpretation were completed on 2 August 1985 and were of a very cursory and informal form. The raw data provided by the contractor and the rough reduction made by EPA were presented to the USIA Health and Safety Officer in a rough set of handwritten and typed data and notes. The conclusions drawn by the EPA person that reviewed the raw data was that all of the target pollutants were well below the "Threshold Limit Value", and that "...none of the reported values approach significance." Unfortunately, the target pollutants of the project did not include the more common forms of gases, e.g., CO_2. As a result, nothing significant was learned from the air sample analysis, except that the air at the sample points during August did not contain any significant amount of the target pollutants listed in Appendix C.

Implications of the Negative Results

The results of this effort tend to reinforce the hypothesis that there is a need to design and include indoor air pollution preventive measures into a building's interior air system. A significant effort was made with no useable results toward identifying the USIA building's air problem. It is, of course, obvious that the target

pollutants and the sampling plan were selected to suit the needs of EPA's program and not the specific needs of the USIA building's air problem. However, the selection of the target pollutants for this building and most other buildings, at any given time of air pollution evidence, would still remain a problem. Determination of long term protection requirements with this approach is virtually impossible. However, the use of air pollutant preventive measures in building air systems remains justified for the short term and is an effective approach for long term protection.

The failure of the chemical approach to detect significant levels of any target pollutants during August also tends to reinforce the summer air migration behavior illustrated in Figure 2. If this same investigation were repeated under cold winter conditions, completely different results would quite likely be determined.

EXTRAPOLATION OF AIR BEHAVIOR TO COOL WEATHER CONDITIONS

Because there was a definite similarity between the theoretical or expected air flow behavior and that which was evidenced by the measured data, under summer or warm weather conditions, it was assumed that the migrational behavior of the building's interior air during winter or cool weather conditions would follow the theoretically expected behavior illustrated in Figure 3. As a result, pollutant gases and particulate matter could be transported from sources below the third floor to occupant spaces above the second floor during winter and cool weather periods. However, such transport during warm weather would be inhibited by the form of the air flow, which is illustrated in Figure 2. Thus, the lack of complaints under warm weather conditions did not necessarily indicate that the exhaust stack modification solved any of the air problems in the building.

Since the complaints occurred during winter or cool weather conditions and the air behavior data were acquired during warm weather conditions, the data measured and collected, relative to the air environment, did not represent the air state within the building as it was at the time of the complaints. All of the other data, such as

the structurally related parametric data, remain valid. Consequently, it is necessary to modify the air environment state data to reflect the air state at the time that the complaint conditions existed, e.g., the external ambient air temperature that would typically exist during the period that the complaints were generated. Using such state data and relevant building parameters acquired during the field work, estimates of interior air movement behavior can be calculated for some of the critical building components along the various air migration paths in the building. These would include the above grade stairwells and elevator shafts, the below grade stairwells and elevator shafts, and the loading dock doors, as a minimum.

Winter Air Behavior in the Above Grade Stairwells

Estimates of the volume flow rates from a typical above grade stairwell to each floor level above the second floor can be calculated based on the following assumptions:

1. That winter leakage flow behavior would be as illustrated in Figure 3.

2. That the average above grade stairwell air temperature is 60°F.

3. That the average building corridor air temperature is 70°F.

4. That the stairwell-corridor doors have an average leakage area of 0.2 square feet.

The estimated air leakage through the stairwell-corridor doors under the above conditions ranges from 31 CFM on the 3rd floor to 188 CFM on the eighth floor. These leakage flows provide transport mechanisms for buoyant pollutants from the lower levels through the stairwells to the upper levels of the building.

Calculated estimates of the negative pressure differentials for the corridors, relative to the stairwells, above the 2nd floor of the building, at the undercuts of the doors and under the above assumed conditions, are as follows:

1. For the 8th floor: .028 inches of water.

2. For the 7th floor: .019 inches of water.

3. For the 6th floor: .015 inches of water.

4. For the 5th floor: .011 inches of water.

5. For the 4th floor: .006 inches of water.

6. For the 3rd floor: .002 inches of water.

the above estimates of winter pressure differentials may be calculated using Equation 4 of Appendix B.

Winter Air Behavior in the Above Grade Elevator Shafts

As in the case of the above grade stairwells, the winter leakage flow behavior of the above grade elevator shafts should be similar to that shown in Figure 3. As a result, the above grade elevator shafts would behave in the same manner as the above grade stairwells relative to providing a transport mechanism for buoyant pollutants from the lower levels to the levels of the building above the 2nd floor.

Winter Air Behavior in the Below Grade Stairwells

Based upon the physical measurement data acquired, related to the leakage paths, and the winter weather conditions assumed above, estimates of air leakage from the garage levels to the first floor range from 7 CFM to 40 CFM for the typical below grade stairwell. This flow would act as a transport mechanism to move buoyant pollutants, such as CO and CO_2, from the garage levels to the first floor lobby of the building.

Winter Air behavior in the Below Grade Elevator Shafts

Assuming that the below grade elevator shafts would follow the theoretically expected behavior, their flow behavior during winter or cool weather conditions would also be similar to that shown in Figure 3.

Winter conditions assumed for the below grade elevator shafts would include consideration of the external exposure of the garage levels. With a nominal 30^{o}F air

temperature in the garage levels, an intermediate temperature on the order of 45°F could be assumed to exist in each of the below grade elevator shafts. A 70°F temperature for the first floor lobby of the building is a good assumption for that space. Using the measured physical leakage path data which had been acquired, estimates of air leakage from the garage levels to the lobby of the first floor through a typical below grade elevator shaft range from 9 CFM to 52 CFM. As in the case of the below grade stairwells, this flow through the below grade elevator shafts would provide a mechanism for buoyant pollutants to be transported from the garage levels to the interior of the first floor of the building.

<u>Winter Air Leakage through the Loading Dock Doors</u>

Since the interior air state of the building during cool or winter conditions would be significantly impacted when the loading dock doors were standing open and that gases from waste materials in the dumpster nearby could easily migrate into the building, estimates of flow through the loading dock doors under nominal winter temperature become of importance.

Assuming, as in the above flow estimates, an exterior atmospheric temperature of 30°F and an average interior building atmospheric temperature of 70°F, the following estimates of flow rates result:

1. With the corridor doors open, the volume flow rate from the loading dock area into the corridor would be approximately 800 CFM, or more.

2. With the corridor doors closed, the volume flow rate from the loading dock area into the corridor ranges between 10 CFM and 65 CFM.

IMPLICATIONS OF ACQUIRED AND ESTIMATED DATA/INFORMATION

The data acquired on 24 May 1984 for the USIA building definitely indicated that the migrational behavior of the interior air conforms to behavior that can be predicted. The only significant perturbation caused by the HVAC system was the serious unbalanced condition that was noted between the north and south systems on almost every floor of the building.

Building Leakage Characteristics

The leakage characteristics of this building were of a typical nature, i.e., their forms, their existence, their locations, their magnitudes, etc. The separation of the above and below grade stairwells and elevator shafts is a good design feature relative to inhibiting the direct migration of air and buoyant products from the below grade garage levels to the upper floor levels of the building. However, it could be made much more effective in accomplishing this function than is presently being achieved. Below grade gases and buoyant particulate matter are merely being detoured through and diluted in the first floor lobby area. They are not being seriously inhibited in their upward journey. The dilution of cold or cool gases flowing from the parking levels need not be significant. With no mixing mechanism existent and with thermal stratification possible, fairly undiluted below grade gases could easily flow at floor level into the above grade shafts. A mixing mechanism is essential to achieve any significant dilutional effect in the first floor lobby area.

HVAC System Effectiveness

As indicated earlier, many sources of buoyant pollutants may be very difficult and expensive to identify and eliminate. However, in all cases, there are effective means to prevent or significantly inhibit the migration of such pollutants into occupant spaces and to reduce their concentrations to insignificant levels. Many design techniques currently exist for air systems to prevent the migration of undesirable odors and buoyant pollutants. Some of these techniques were not being accomplished by the performance of the USIA building's HVAC system.

The building's HVAC system is a major contributor to the existence of buoyant migration paths into occupant spaces because of unsuitable pressure relationships between interior spaces, primarily between corridors and occupant spaces. Adjusting the HVAC system to perform so that occupant spaces are always at a higher pressure than their adjacent corridors would prevent much of the undesired migration of real or potential buoyant pollutants into these spaces. Similarly, maintaining pressure differentials between all vertical shafts and horizontal paths, such as corridors, in a manner that would prevent flow from the shafts to the corridors is also an effective

preventive measure. Other pollutant transporting mechanisms can be, in general, eliminated or minimized fairly simply.

Improper Pressure Relationships of Occupant Spaces

The existence of the negative pressures in rooms 504 and 536, relative to their adjacent corridors, fully explains why these spaces were the worst and most continuous source of complaints. It is also excellent evidence that the corridors adjacent to these two spaces are part of the migration route from the source(s) of the buoyant pollutants to these spaces. In addition, and related to the susceptibility of room 504 to infiltration from its adjacent corridor or any other adjacent migration path, this room had an absolute minimum air supply at the time of the field investigation.

As indicated earlier, the positive pressure differentials between room 416, 518, 822 and 848, and their adjacent corridors were very small, i.e., marginal. Small changes in the HVAC system operation and/or the external atmosphere would easily reverse the direction of the pressure difference and the resulting air flow, i.e., so that corridor air would flow into these spaces.

Vertical Shaft Infiltration of the Upper Levels

Even though very small buoyancy forces existed during the field investigation, it was clearly evident from the data that classic stack effect conditions existed in all of the above grade shafts, and reverse stack effect. There was a definite and consistent negative pressure relationship of the 8th floor with all of the above grade stairwells and elevator shafts.

Further, the measured data imply that the actual upper neutral plane was at or near the deck of the 6th floor. A small increase in pressure within these shafts would clearly produce a negative pressure differential condition with the 6th and 7th floors, relative to the shafts. Because of the need to achieve an equilibrium pressure condition in these shafts, a low pressure air space will be found, i.e., via leakage paths. Thus, it is usually not possible in most buildings to avoid migrational air flow via vertical shafts because of the manner in which they are designed and constructed. However, if air exhaust, not return air but 100% exhaust to the outside,

is provided at the top of such vertical shafts of adequate volume rate, all floors during all seasons can be maintained in a positive pressure relationship with these shafts. This results in air flow from all floor levels into the shafts in all seasons. This would prevent infiltration of buoyant pollutants from these shafts to any floor. Instead, such pollutants would be exhausted to the outside atmosphere. However, if pressurization of stairwells and elevator shafts occurs or is desired for smoke control purposes during a fire, such exhausts would need to be effectively stopped and the exhaust ducts sealed during the smoke control mode of operation. An acceptable alternative design approach would be one that uses a reversible flow design or reversible fan. Such a design would reverse flow direction on fire detection and support pressurization of these shafts for smoke control purposes.

Cold Weather Recurrence of Complaints

It is important to point out that, if suitable corrective measures are not instituted in the USIA building, there is a high probability that complaints will continue to occur during all winter or cool weather conditions.

RECOMMENDED CORRECTIVE MEASURES

Measures recommended for the solution of the indoor air pollution problems of the USIA building are of two levels, as follows:

1. To provide immediate but temporary relief to USIA employees.

2. To provide long term protection from future recurrence of similar problems.

Temporary Measures

Immediate relief can be achieved for the complainants by adjusting air supply and return air volume rates. However, such adjustments should not be viewed as permanent corrective measures. In fact, such adjustments could induce air problems in other parts of the building. Consequently, the recommended permanent measures are not only a protection against future similar problems, but they will also insure that the present indoor air problems are not diverted elsewhere within the building.

The recommended measures for immediate relief to the workplaces with identified problems are as follows:

1. Adjustment of the north and south HVAC systems to eliminate the high volume rate flow from the south wing to the north wing on all floors of the building.

2. Adjustment of the air supply to room 504 to achieve:

    a. A significant increase in the air change rate of that space.

    b. A definite positive pressure differential over the adjacent corridor air pressure.

3. Adjustment of the air supplies to rooms 416, 518, 536, 822 and 848 to achieve definite pressure differentials over the air pressures of their respective adjacent corridors.

Permanent Measures

A substantial improvement in the interior air environment of the building can be achieved without new equipments or modifications to the building. The field investigation clearly indicated that the building's air system is substantially out of balance. Consequently, the first and most important step that should be taken is to balance the building's air system. This should result in the air system performing to its design objectives. The following improvements should also be achieved with such balancing:

1. Elimination of the high volume flow from the south wing to the north wing on all levels.

2. Establishment of an adequate air supply to all workplaces.

3. Establishment of air pressures in all workplaces that adequately exceed adjacent corridor air pressures. Approximating calculations indicate that a minimum pressure differential of .03 inches of water pressure should be maintained in the workplaces over adjacent corridor pressures.

It is of importance to realize that maintenance of a balanced building air system is a continuing function. It cannot be performed once and expected to last for the lifetime of a building.

In addition to balancing the air system, two other measures must be accomplished without fail on a continuing basis. They should be performed in a standard and routine manner. These measures are as follows:

1. Performance of adequate cleaning and changing of HVAC system filters.

2. Providing adequate intake of fresh outside air to the HVAC system. This is essential to the maintenance of an adequate level of O_2, and safe levels of CO and CO_2.

Prevention of Above Grade Vertical Migration - Thermally driven pollutant carrying air flowing into the corridors of the upper floors from the above grade shafts can only be prevented by eliminating the infiltration mechanism. Since this mechanism exists because of pressure differentials, the simplest and most certain preventive measure is to maintain the above grade vertical components of the migration paths at pressures lower than possible on the 8th floor. In determining this pressure, worst case conditions should be assumed, such as, the coldest expected atmospheric temperature.

Providing such pressures in the above grade shafts must be definite and consistent. Simple venting does not provide a definite and consistent pressure relationship between the above grade vertical shafts and the connecting upper floors. Installation of adequate exhaust fans at or near the top of the above grade vertical shafts would provide definite and consistent pressure relationships with the connecting floors.

If these shafts are subsequently provided with pressurizing smoke control systems, particularly the stairwells, the operation of these exhaust fans would need to be terminated on detection of a fire, and tight dampers closed in the exhaust ducts. An alternative design approach would be to provide reversible fans or reversible flow, and integrate these fans into the smoke control system.

Prevention of Below Grade Vertical Migration - The same vertical migration problem exists in the below grade stairwells and elevator shafts, as exists in the above grade shafts. However, preventing vertical migration in the below grade shafts is most simply and effectively accomplished by pressurization of these shafts with either conditioned air or fresh outside air.

The pressure provided in these shafts must exceed the highest possible pressure achievable on the lowest parking level under the coldest atmospheric temperature and dynamic wind pressure effect. This approach totally prevents the infiltration of these shafts by parking level air/gases and/or buoyant particulate matter. Since the air used for pressurization would be good air, losses to the lobby area would not be harmful.

Recommended Designs of Fan Modifications - Designs for the above recommended fan modifications to the above and below grade stairwells and elevator shafts are presented in Appendix D. Cost estimates to accomplish these modifications, and the balancing and adjusting of the HVAC system are also presented in Appendix D.

Recommended Winter Investigation

While the recommended corrective measures are well justified, it was also recommended that the same form of air behavior field investigation performed in May 1984 be performed under cold weather conditions. Such an effort would also include any investigation necessary for new complaints received from employees in spaces different from those already identified.

APPENDIX C

EPA INDOOR AIR POLLUTION PROJECT

SAMPLING PLAN

TABLE C-1. MONITORING STRATEGY

Compound	Sampling/Analytical Method	Monitoring Schedule
Group I (Volatile Organics)		
α-Pinene n-Butylacetate Ethoxyethylacetate Cresol Toluene[a] Xylenes Ethylbenzene Trimethylbenzene Styrene n-Decane n-Undecane n-Dodecane	Collection on Tenax GC/ analysis by GC/MS.	Six consecutive 12 h samples at three locations in each building and one outside site.
Group II (Halogenated Volatile Organics)		
1,2-Dichloroethane 1,1,1-Trichloroethanes Trichloroethylene Tetrachloroethylene 1,1,2,2-Tetrachloroethane Carbon tetrachloride Epichlorohydrin Bromodichloromethane Chlorobenzene Dichlorobenzene	Collection on Tenax GC/ analysis by GC/MS.	Six consecutive 12 h samples at three locations in each building and one outside site.

TABLE C-1. MONITORING STRATEGY (CONT.)

Compound	Sampling/Analytical Method	Monitoring Schedule
<u>Group III (Nitrosoamines)</u>		
Dimethyl nitrosamine Nitrosomorpholine	Collection on Thermosorb/N sorbent/analysis by GC with Thermo Energy Analyzer (TEA).	Six consecutive 12 h samples at three locations in each building and one outside site.
<u>Group IV (Miscellaneous Organics)</u>		
Ethylene oxide Acrylonitrile 2-Propanone 2-Butanone *n*-Propanol *n*-Butanol Vinyl chloride Acrolein Chloroform Vinylidene chloride Phenol	Collection on charcoal cartridges/analysis by GC/FID or GC/ECD.	Six consecutive 12 h samples at three locations in each building and one outside site.
<u>Group V (Pesticides and PCBs)</u>		
Chlorodane PCBs Dichlorvos Ronnel Chloropyrifos Diazinon Malathion γ, β, and α-Hexachlorocyclohexane (BHCs)	Collection on polyurethane foam/analysis by GC/ECD and GC/FPD.	Six consecutive 12 h samples at three locations in each building and one outside site.

TABLE C-1. MONITORING STRATEGY (CONT.)

Compound	Sampling/Analytical Method	Monitoring Schedule
Group VI (Metals)		
Cadmium Bromine Lead Manganese Arsenic Chromium Nickel Aluminum	Collection on 0.3 µm filters/ analysis by PIXE.	Three consecutive 24 h samples outside and at two locations in each building.
Beryllium	Collection on 0.3 µm filters/ analysis by AA.	
Group VII (Polynuclear Aromatics)		
Inhalable particulate mass	Collection on ≤ µm and 3-15 µm particulate matter filters/ analysis by weighing.	Three consecutive 24 h samples outside and at two locations in each building.
Quinoline/Isoquinoline Benzo(a)pyrene Benzo(a)anthracene Benzo(k)fluoranthene Chrysene Fluoranthene Pyrene	Collection on filters/analysis by GC/FID or GC/PID.	
Group VIII		
Formaldehyde	Collection on molecular sieve/ pararosaniline method of analysis.	Three consecutive 24 h samples at four locations.

TABLE C-1. MONITORING STRATEGY (CONT.)

Compound	Sampling/Analytical Method	Monitoring Schedule
<u>Group IX</u>		
Radon	Exposure of Track-Etch^{R} passive monitor/analysis by microscopy.	Two samples collected over a 3-month period.
<u>Group X</u>		
Air exchange	Release of tracer gas/ SF_6 collection of air samples in syringes/ quantitation of SF_6 using GC/ECD.	Continuous measurement for 72 h at three inside locations.
<u>Group XI</u>		
CO	Electrochemical ambient air personal monitor.	Continuous measurement for 72 h at four locations.
<u>Group XII</u>		
NO_2	Chemiluminescent ambient air analyzer.	Continuous measurement for 72 h at four locations.
<u>Group XIII</u>		
Asbestos	Sampling on Nucleopote filters/analysis by TEM.	One 72 h sample at two locations in each building.

APPENDIX D

DESIGNS & COST ESTIMATES

for

MODIFICATIONS

to

IMPLEMENT CORRECTIVE MEASURES

in the

USIA HEADQUARTERS BUILDING

DESIGN OF MODIFICATIONS

A reduced set of drawings representing the USIA building are presented in Figures D-1 through D-16. The drawings and specifications for the design of the modifications necessary to provide the recommended pressure conditions in the building's above grade stairwells and elevator hoistways are presented in Figures D-17 and D-18. The designs for the modifications to the above grade stairwells and elevator hoistways are planned as rooftop installations.

The modifications necessary to provide pressurization of the below grade stairwells and elevator hoistways are planned to be merely wall or ceiling mounted dome fans that would provide conditioned interior air directly to these shafts. A dome fan with a 20 inch blade of 1/4 hp at 1050 RPM that produces 3/8 of an inch of static pressure is adequate for each of these shafts. An alternate approach is to install utility fans equivalent to the 10FC Trane utility fan as wall or ceiling mounts.

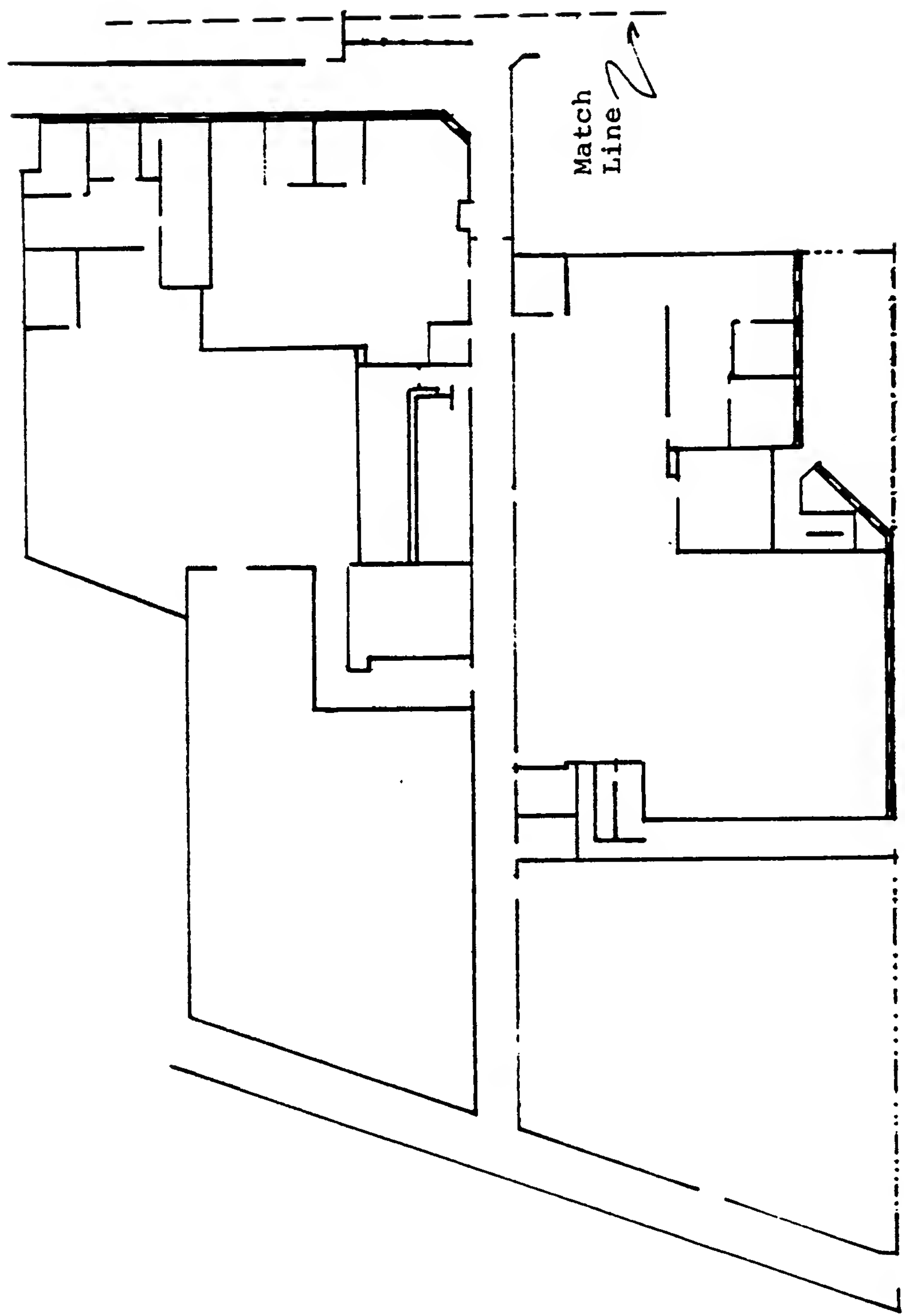

FIGURE D-1. USIA BUILDING FIRST FLOOR-SOUTH

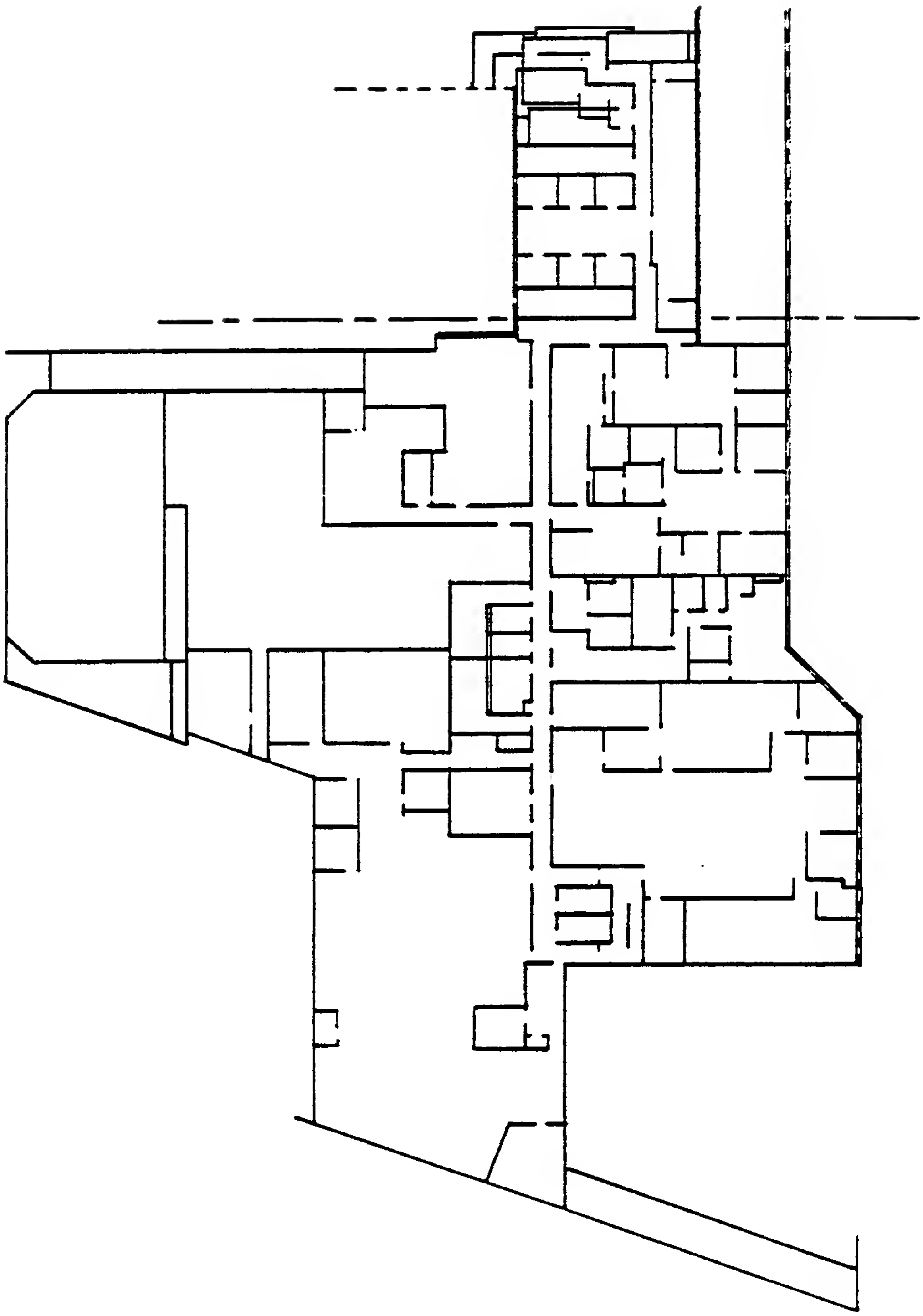

FIGURE D-2. USIA BUILDING MEZZANINE LEVEL

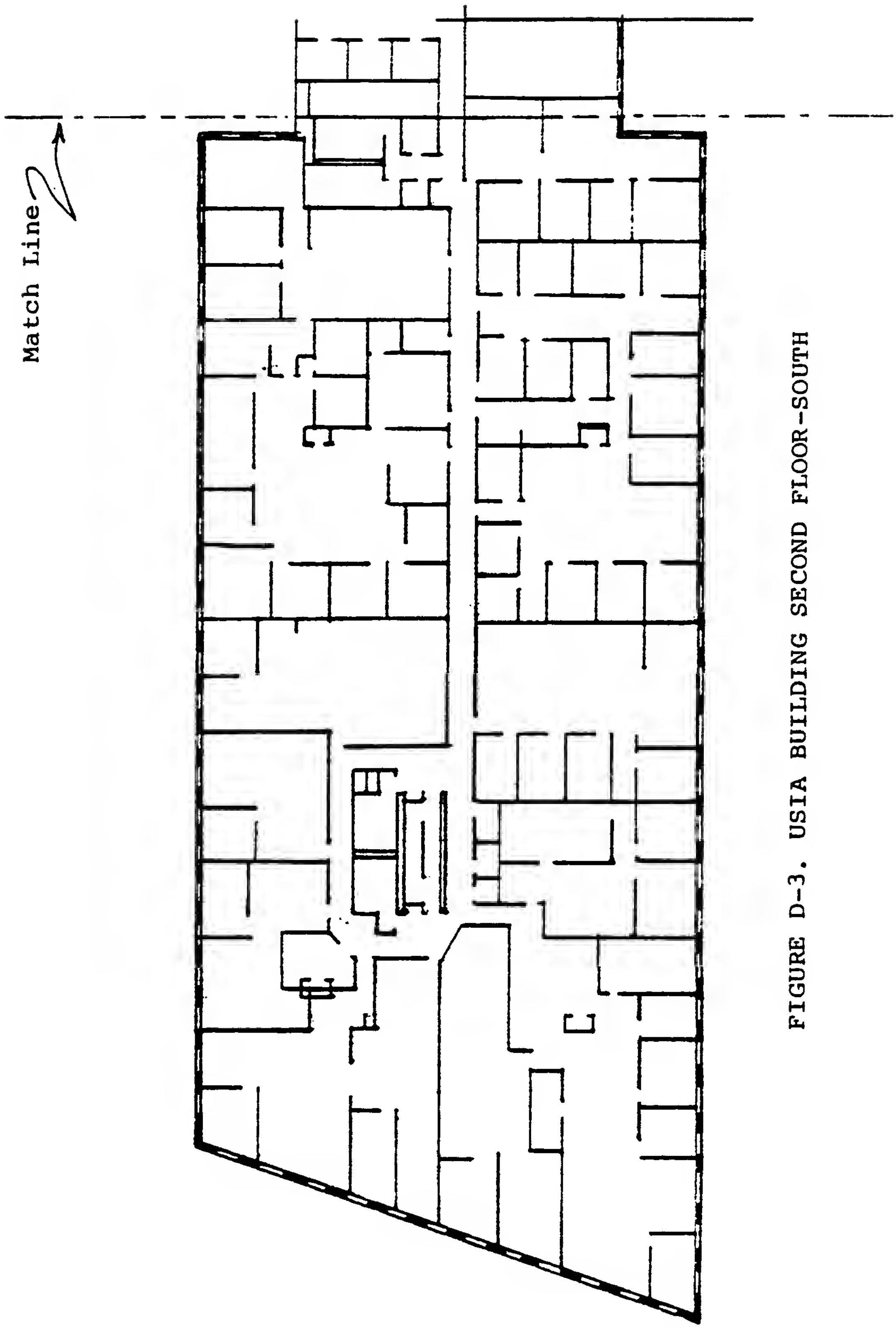

FIGURE D-3. USIA BUILDING SECOND FLOOR-SOUTH

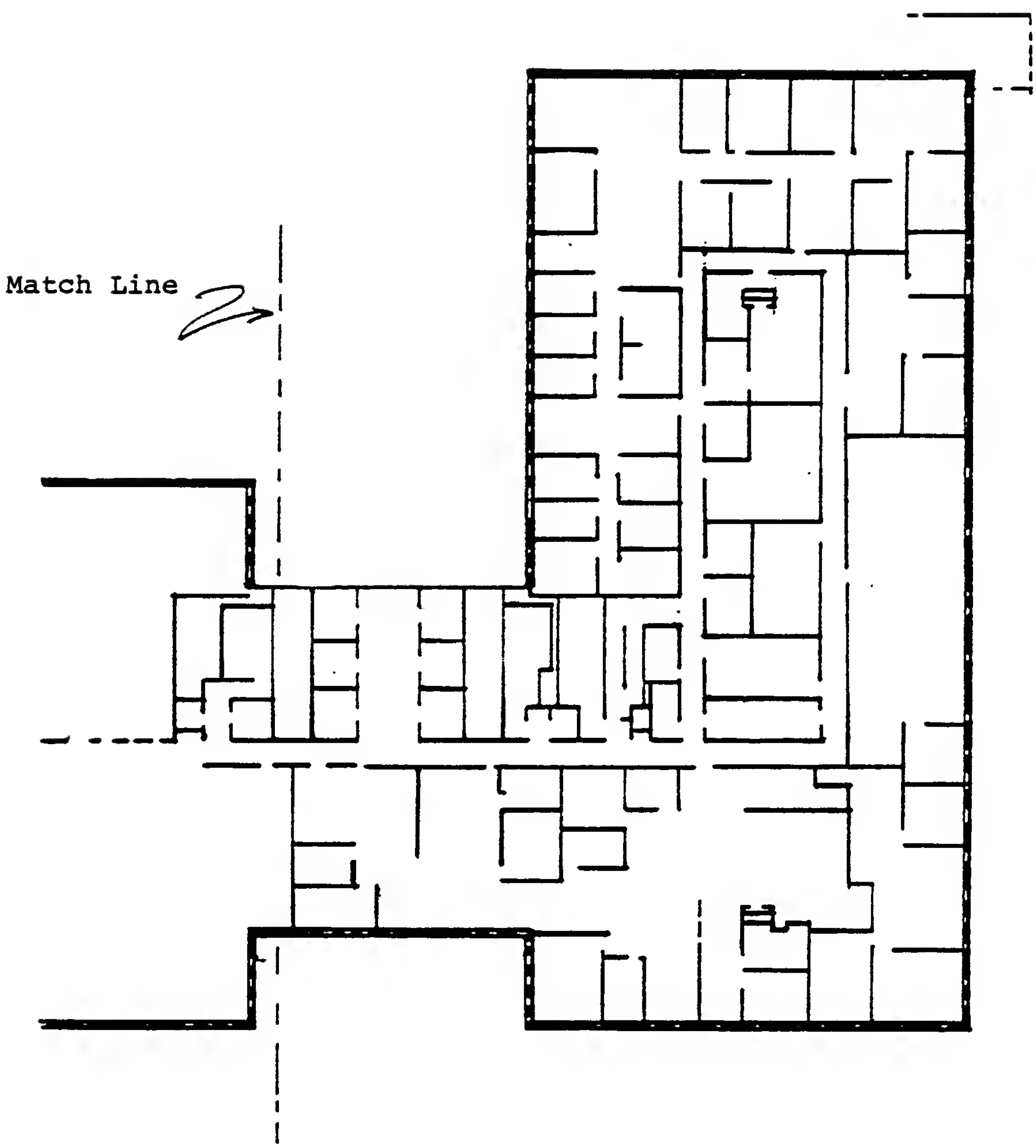

FIGURE D-4. USIA BUILDING SECOND FLOOR-NORTH

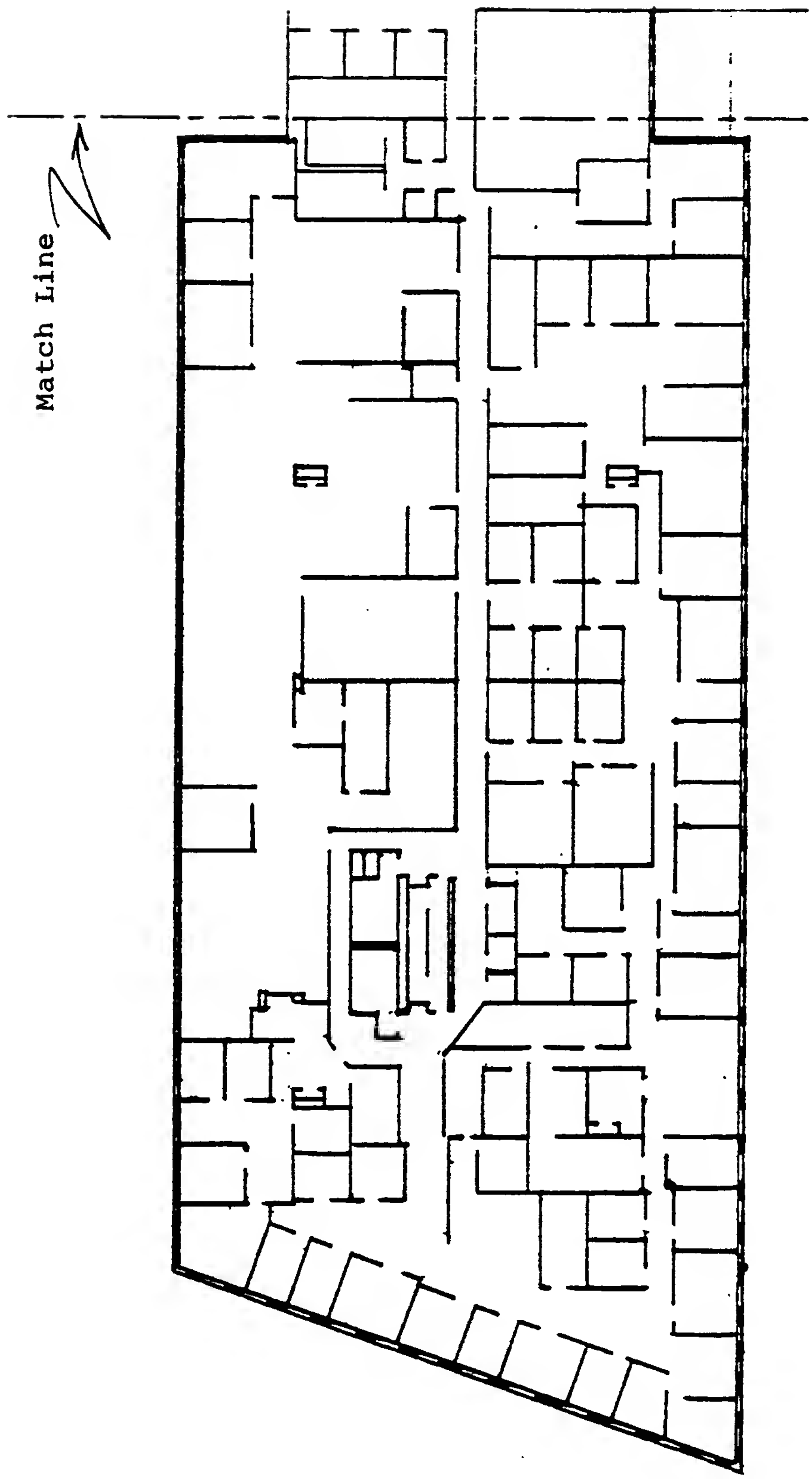

FIGURE D-5. USIA BUILDING THIRD FLOOR-SOUTH

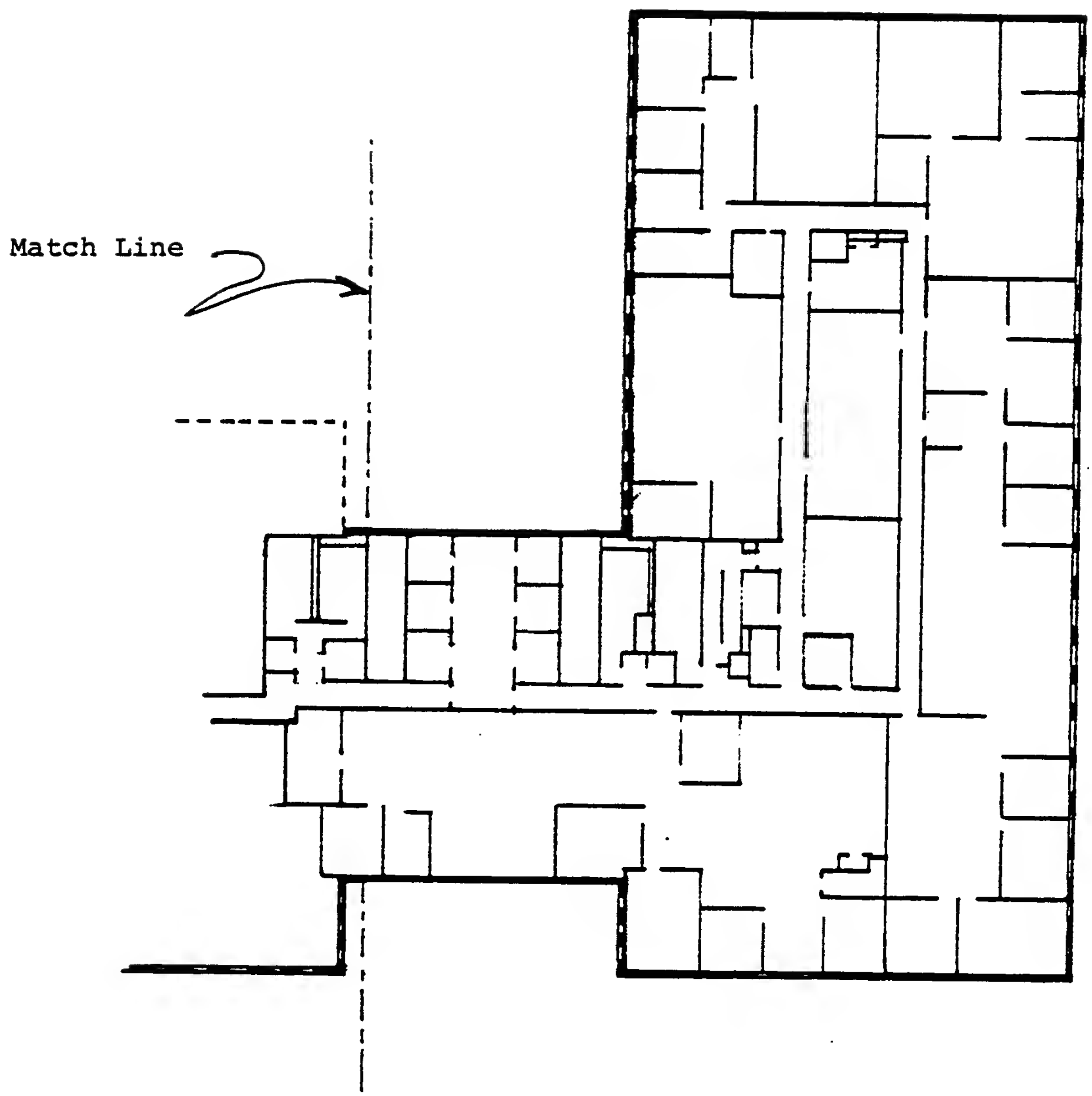

FIGURE D-6. USIA BUILDING THIRD FLOOR-NORTH

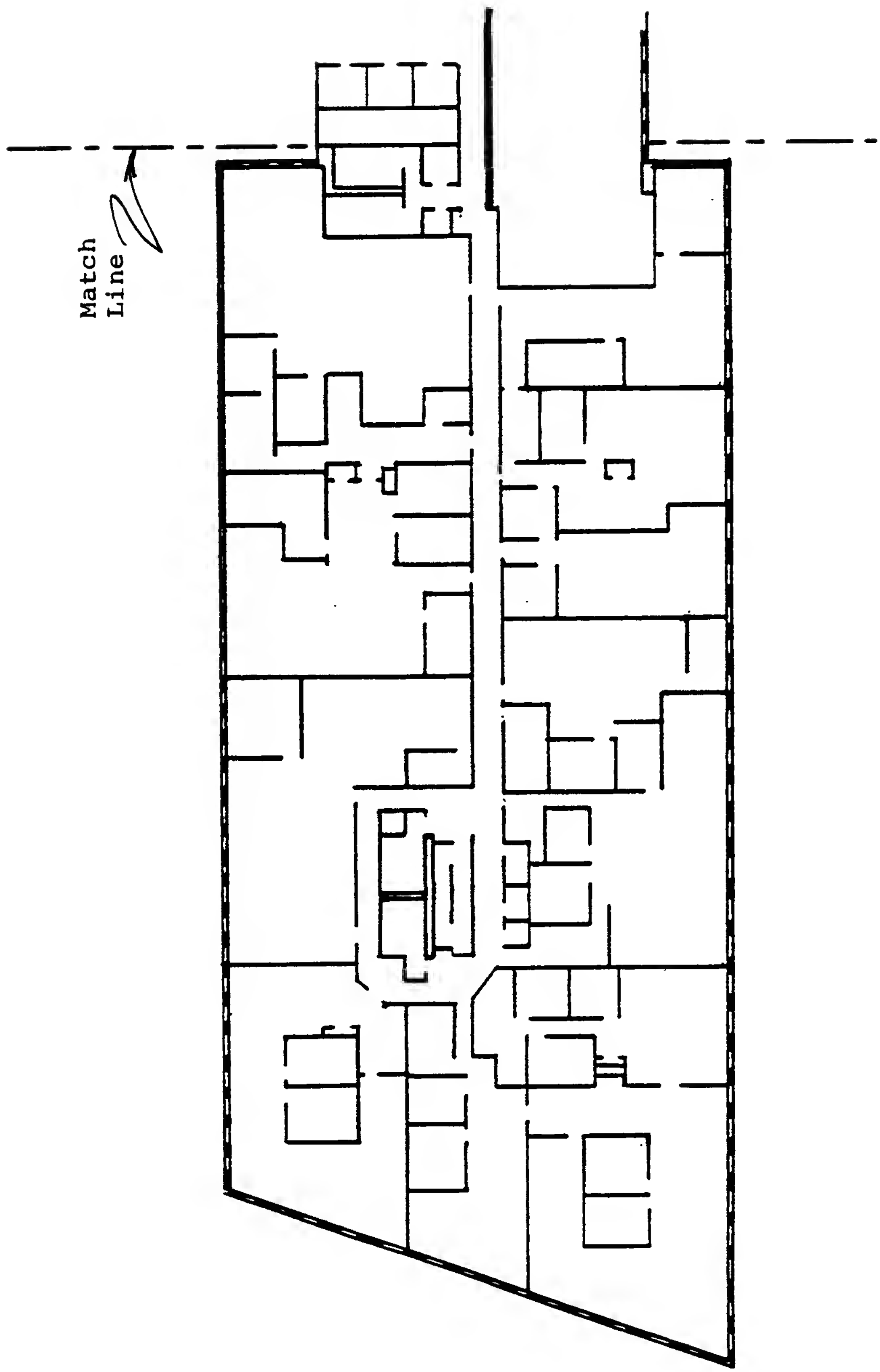

FIGURE D-7. USIA BUILDING FOURTH FLOOR-SOUTH

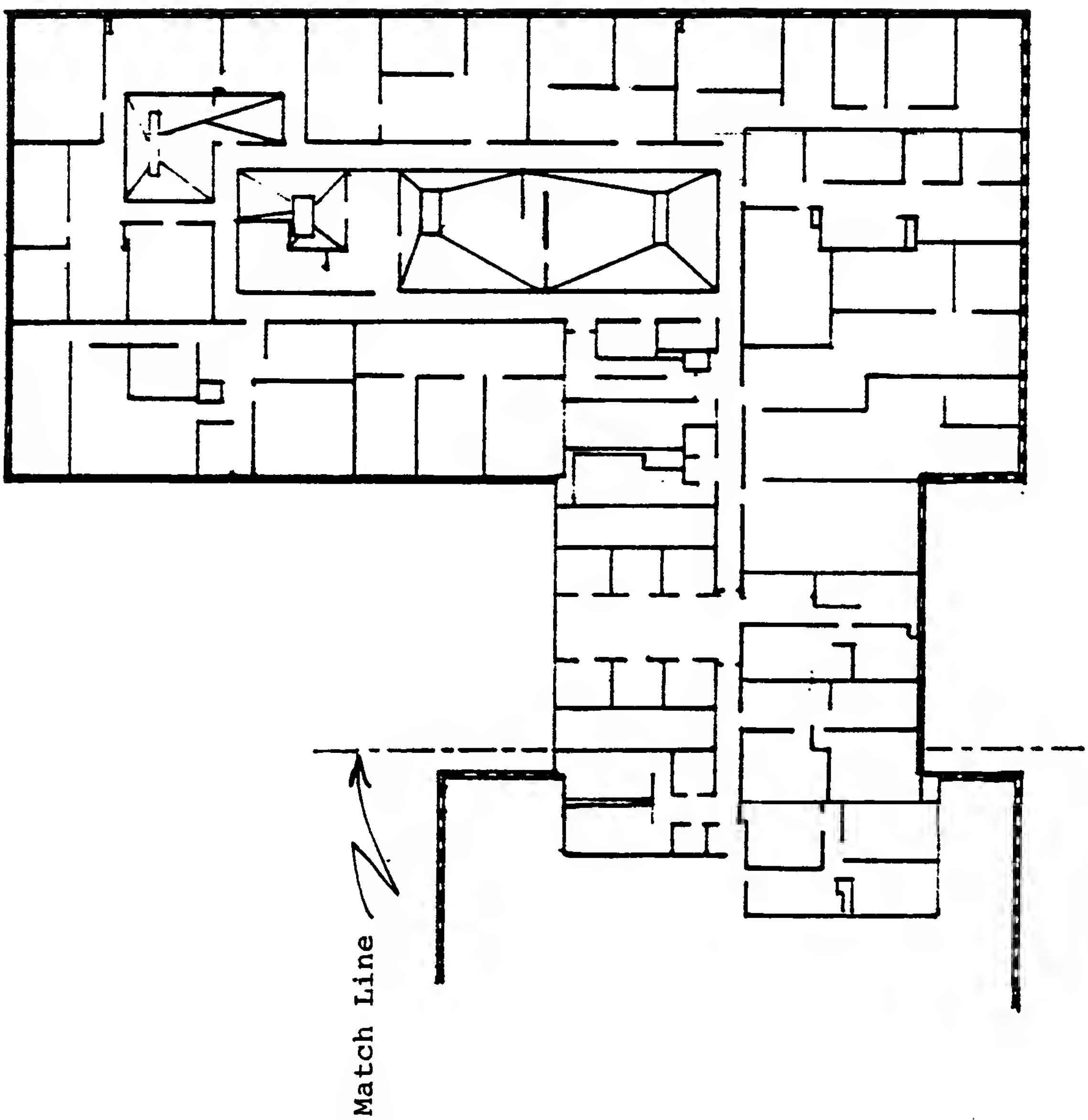

FIGURE D-8. USIA BUILDING FOURTH FLOOR NORTH

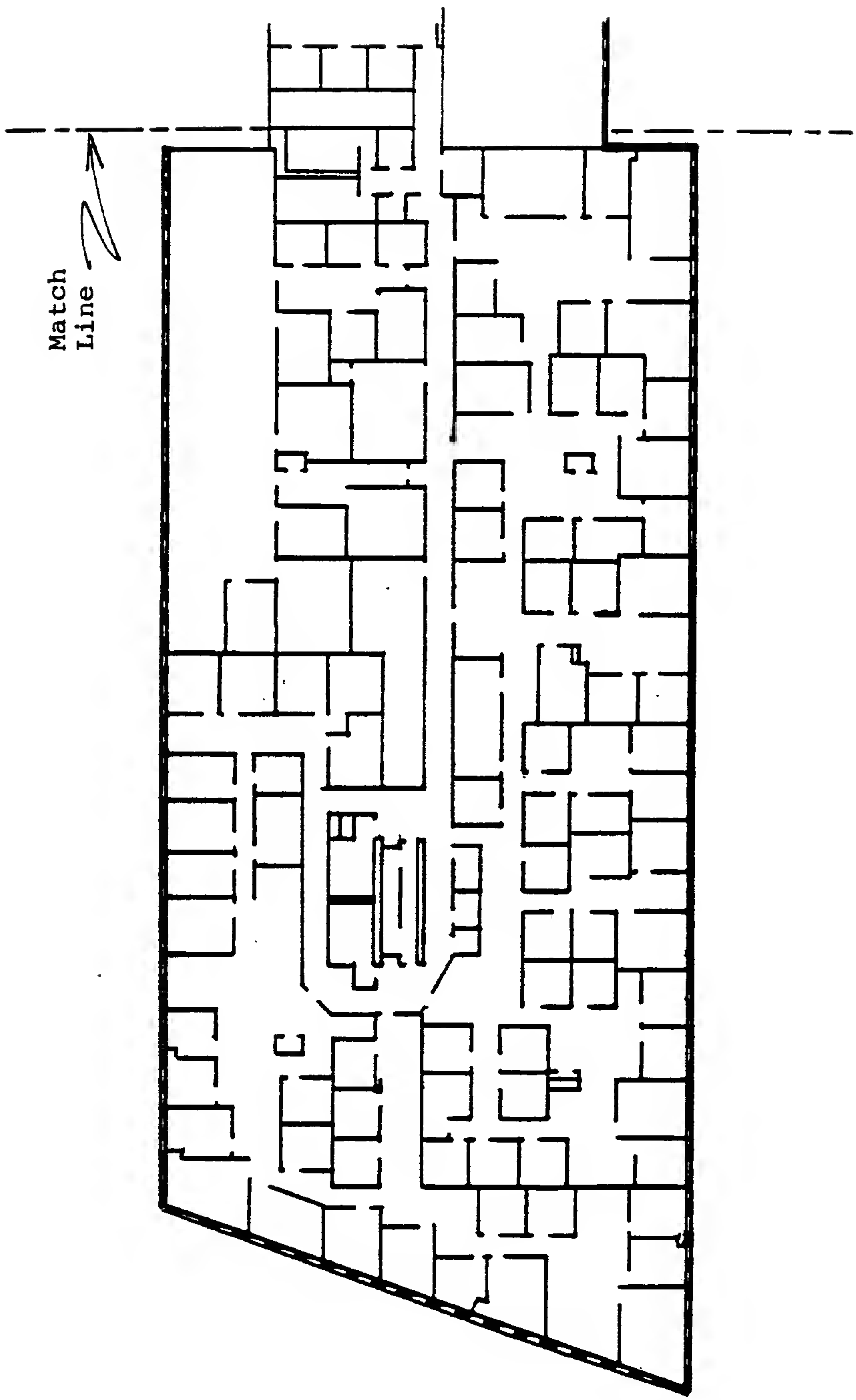

FIGURE D-9. USIA BUILDING FIFTH FLOOR-SOUTH

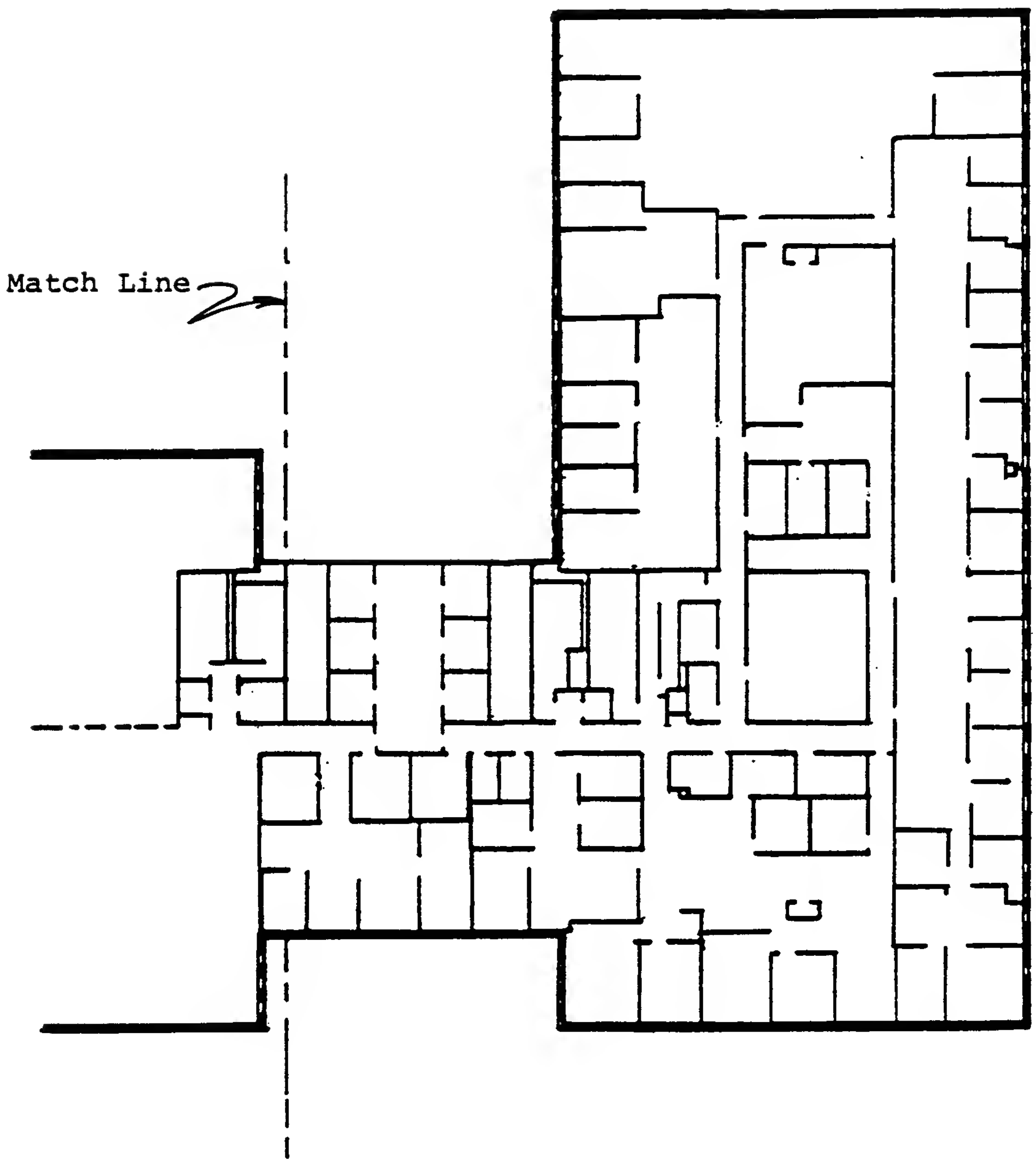

FIGURE D-10. USIA BUILDING FIFTH FLOOR-NORTH

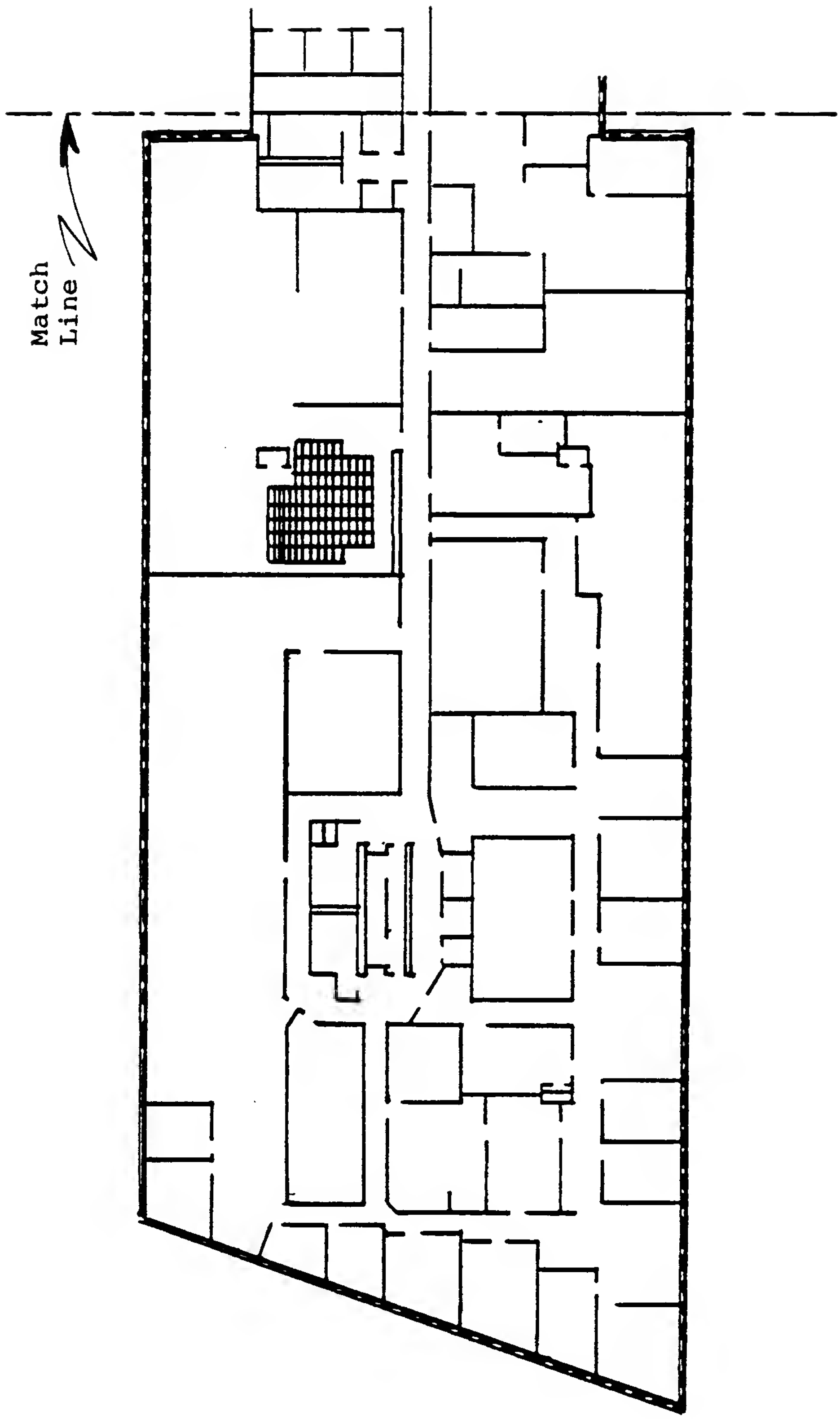

FIGURE D-11. USIA BUILDING SIXTH FLOOR-SOUTH

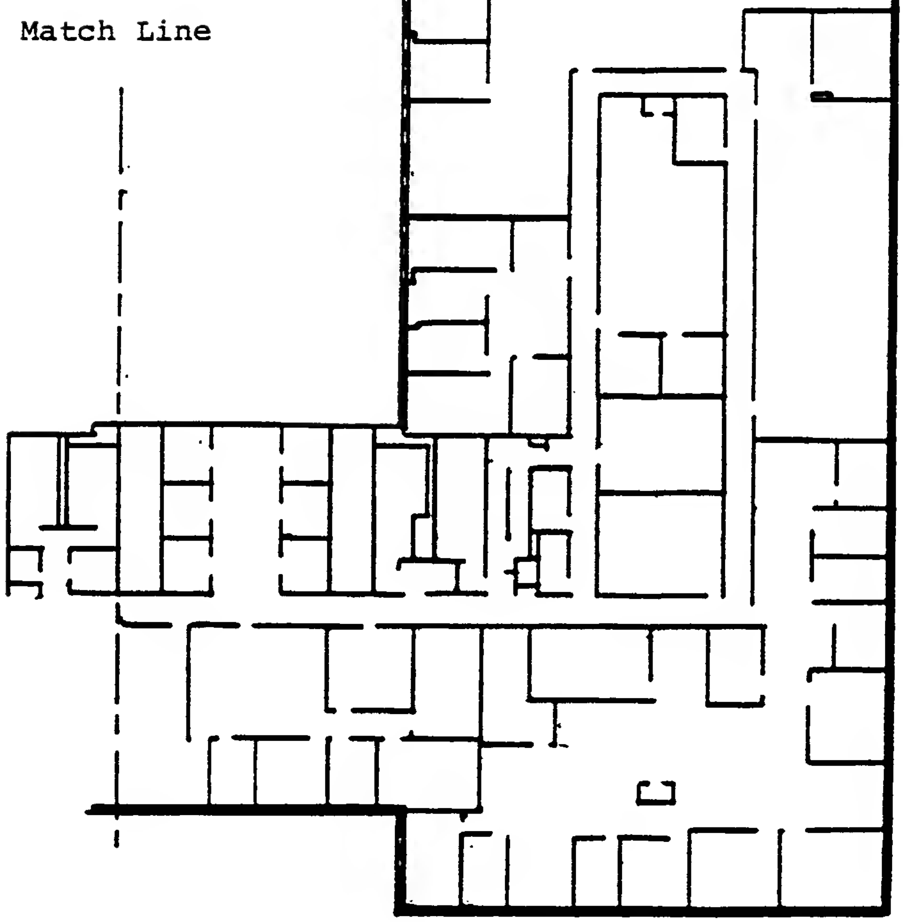

FIGURE D-12. USIA BUILDING SIXTH FLOOR-NORTH

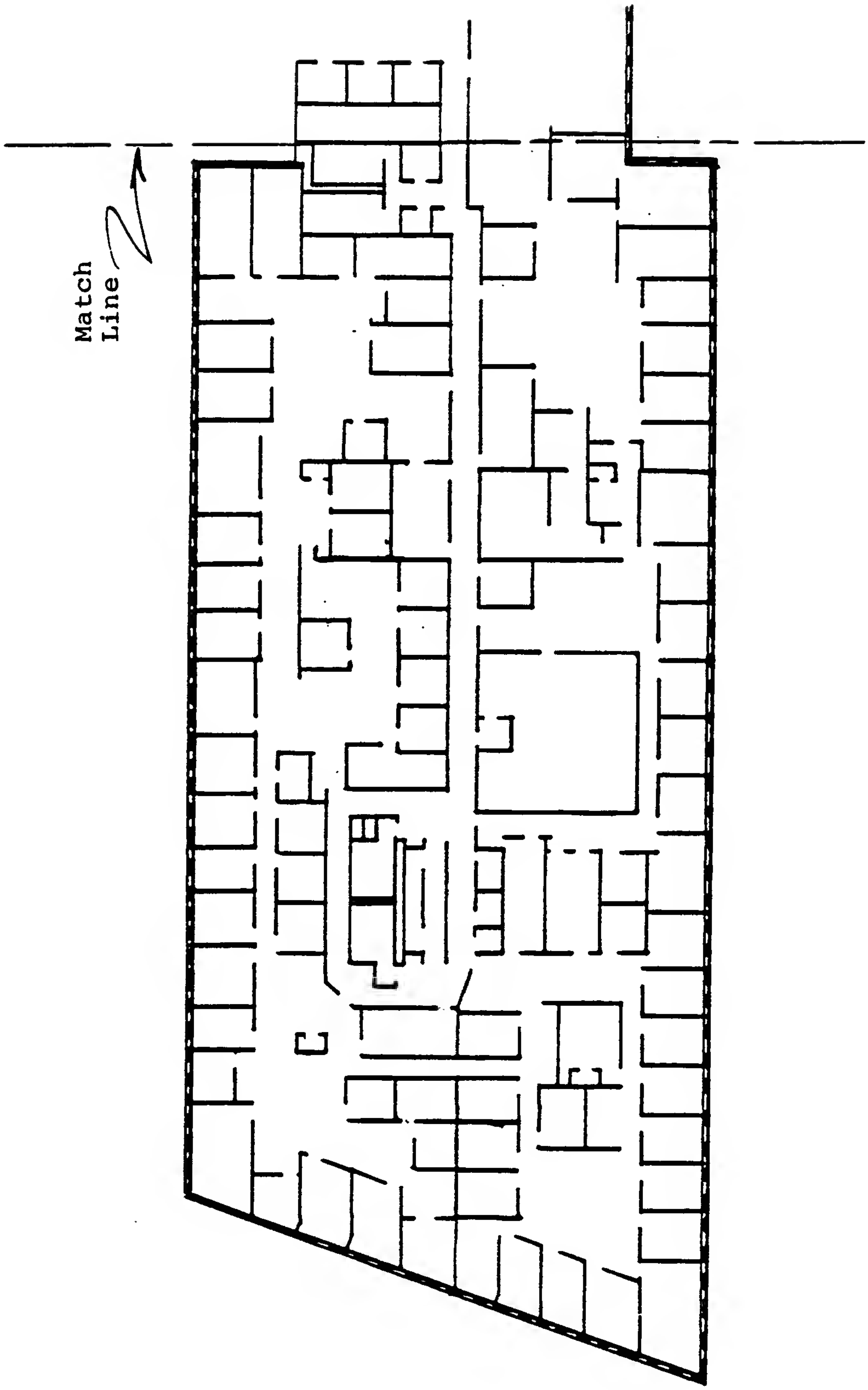

FIGURE D-13. USIA BUILDING SEVENTH FLOOR-SOUTH

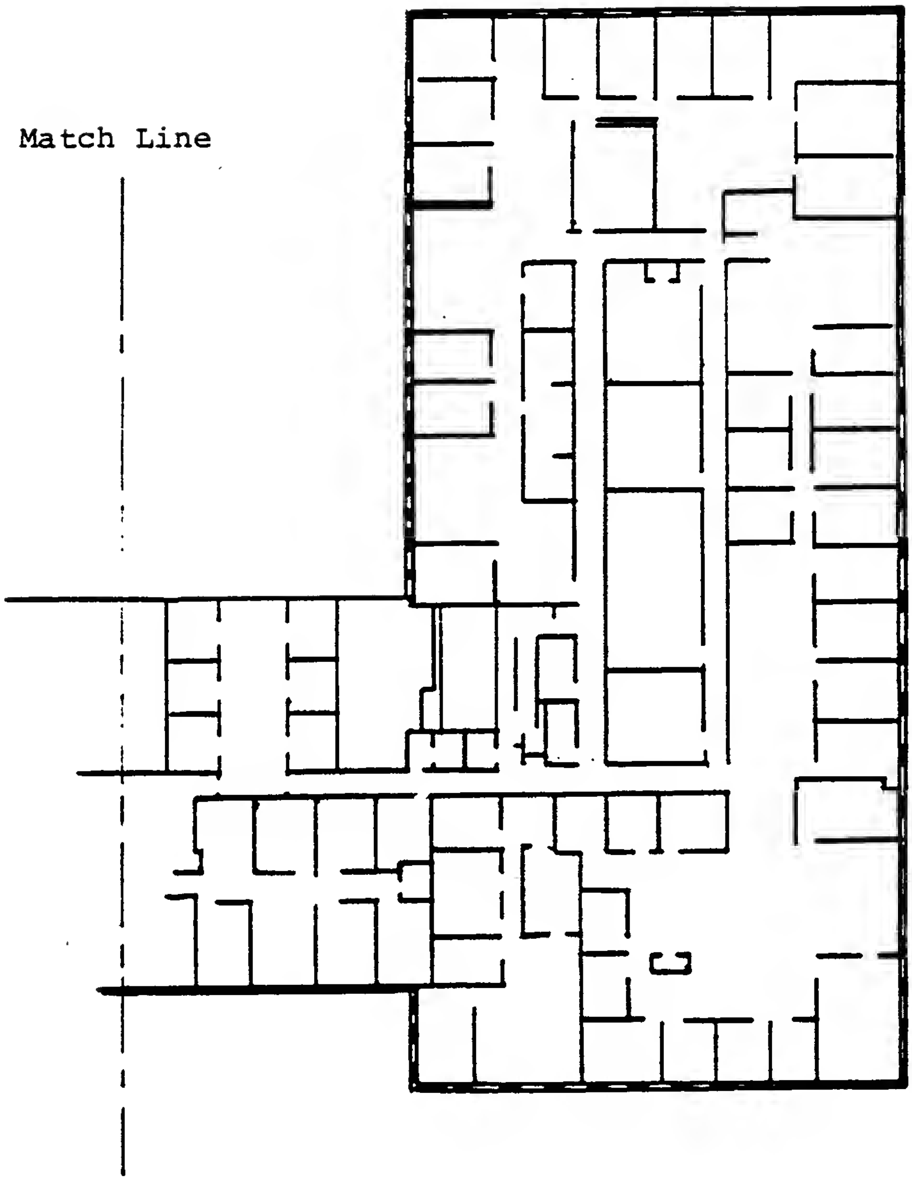

FIGURE D-14. USIA BUILDING SEVENTH FLOOR-NORTH

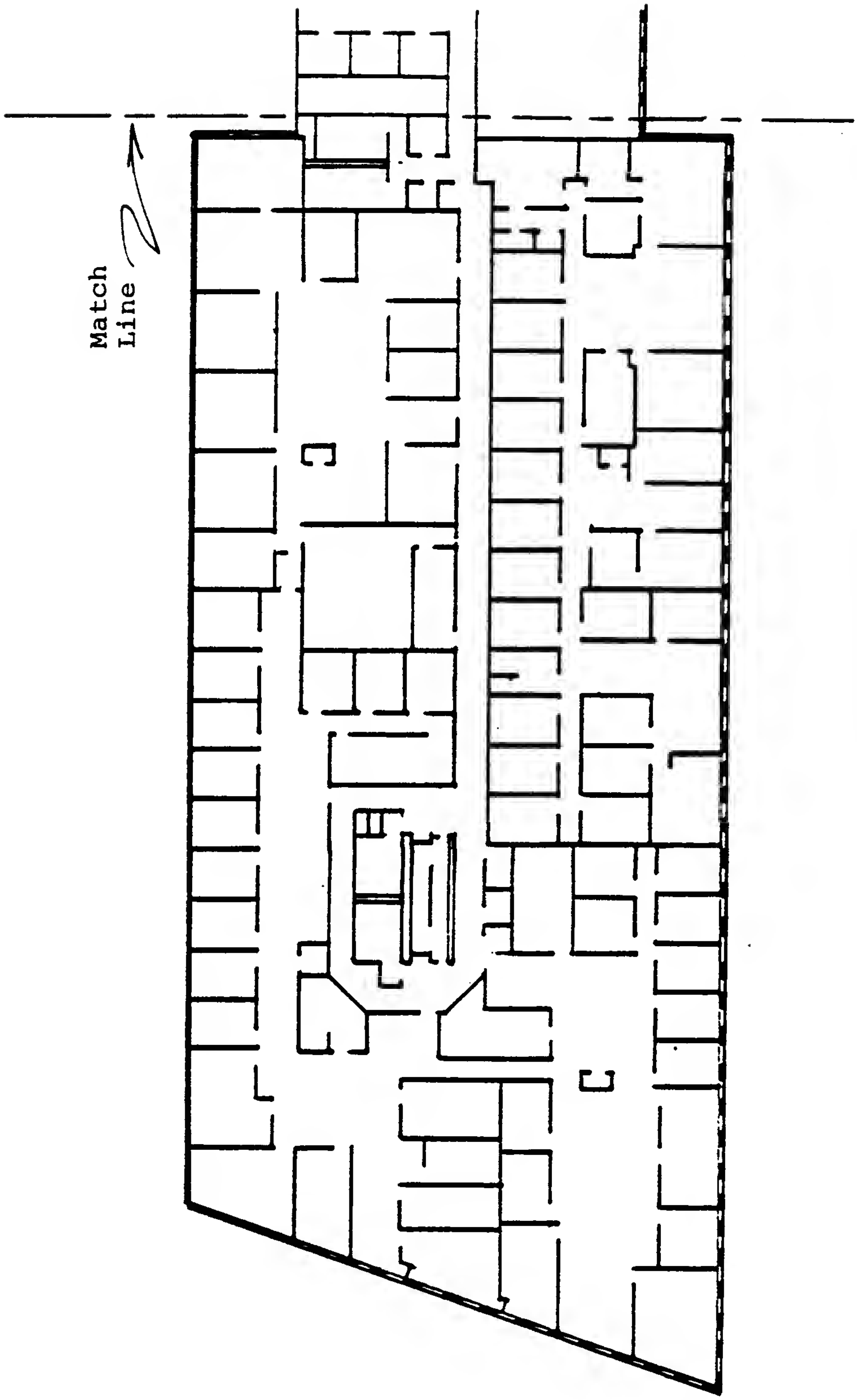

FIGURE D-15. USIA BUILDING EIGHTH FLOOR-SOUTH

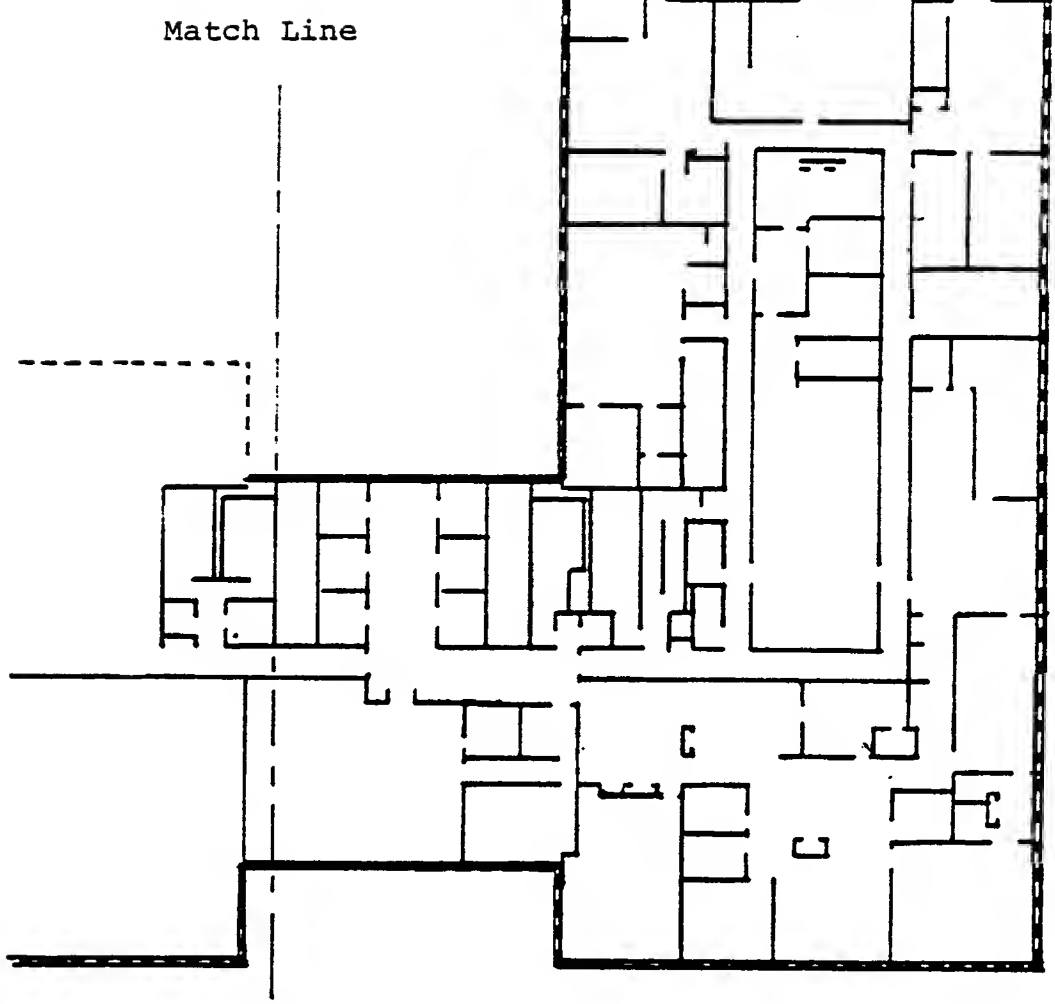

FIGURE D-16. USIA BUILDING EIGHTH FLOOR-NORTH

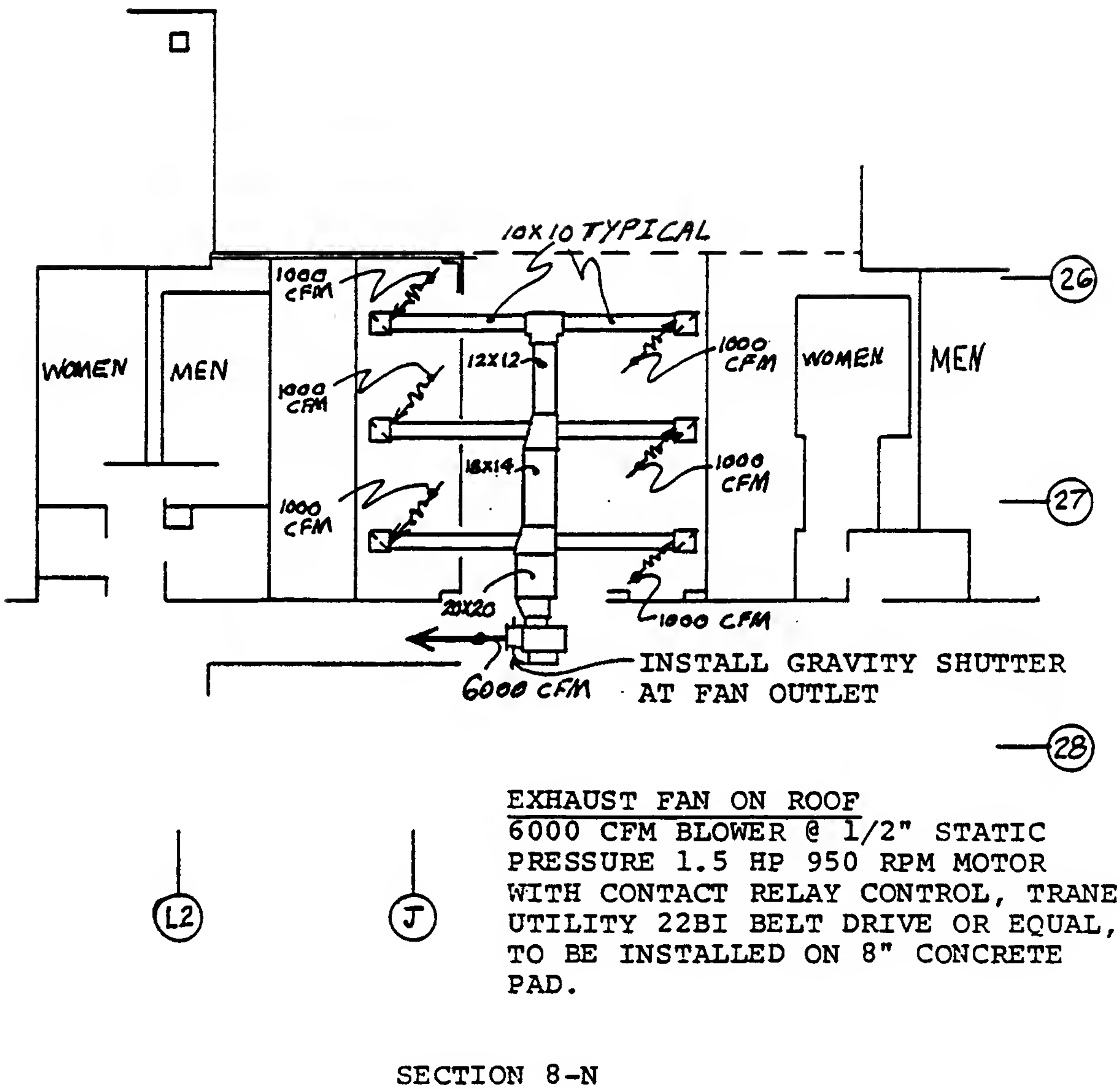

FIGURE D-17. ABOVE GRADE ELEVATOR EXHAUST SYSTEM

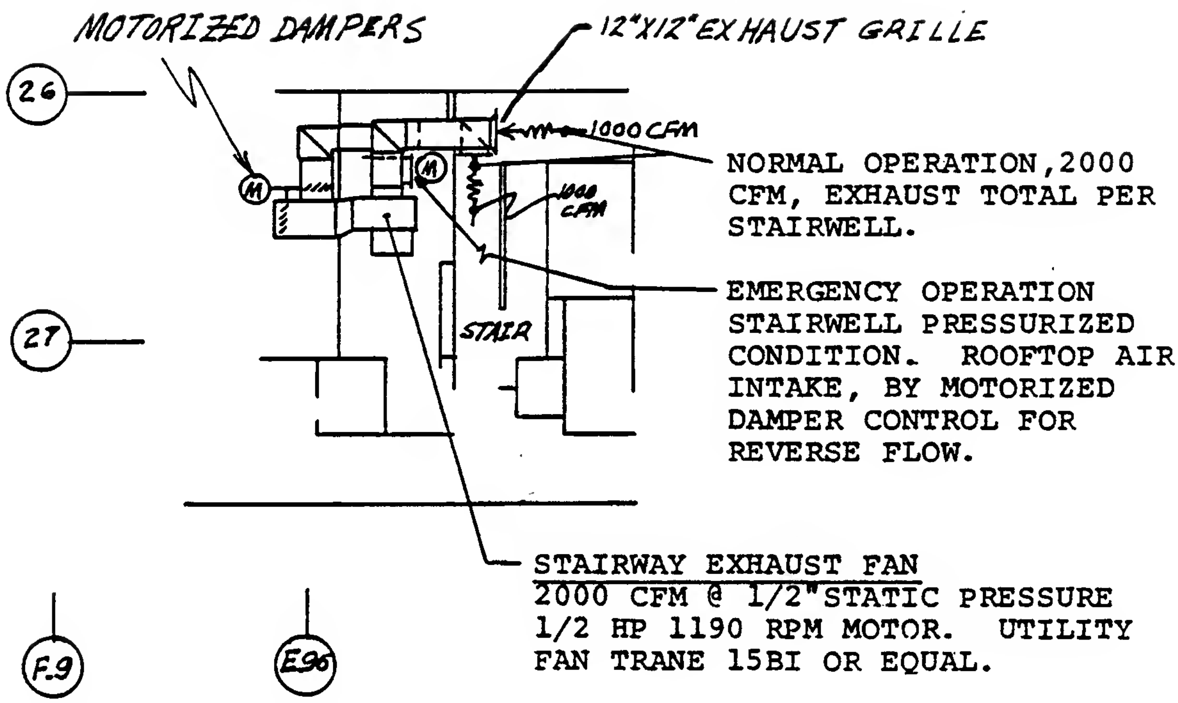

FIGURE D-18. TYPICAL STAIRWELL EXHAUST SYSTEM

COST ESTIMATES

There are five major items that must be considered in estimating the cost for implementation of the recommended measures to prevent migration of air pollutants within the USIA building to occupant spaces. These are as follows:

1. Balancing and adjusting the building's air system, i.e., the HVAC system.

2. Installation of an air exhaust system in each of the four above grade stairwells.

3. Installation of an air exhaust system in the six above grade elevator hoistways.

4. Installation of an air pressurization system in each of the two below grade stairwells.

5. Installation of an air pressurization system in each of the two below grade elevator hoistways.

The above cost elements are for the measures recommended for permanent correction of the air problem(s). The recommended temporary measures were not included in this cost estimate because the permanent measures are of small magnitude and can be accomplished in a short period of time.

In addition to the above initial implementation cost elements, there are continuing costs related to the opertion and maintenance of the above grade exhaustion and the below grade pressurization equipments. These costs are discussed later in this section.

COST ESTIMATES FOR MODIFICATIONS

The cost estimates for the above listed five (5) cost elements and the total for all of those elements are estimated to be as follows:

1. Balancing and adjusting of the total HVAC system, i.e., the north and south systems on each level of the building and all other air handling equipments: $10,000.

2. Installation of an air exhaust system, with a pressurizing reversible mode for smoke control during fires, in each of the four above grade stairwells: $25,000.

3. Installation of an air exhaust system with a cut-off for fire emergencies in each of the six above grade elevator hoistways: $9,000.

4. Installation of four pressurizing fans in the below grade stairwells and elevator hoistways: $4,000.

The total estimated cost for the above items is $48,000.

BALANCING AND ADJUSTING ESTIMATE BASIS

The estimate for balancing and adjusting the building's HVAC system is based upon a balancing cost of $100 per 1,000 CFM and a total volume rate estimate of approximately 60,000 CFM. The total volume rate is based upon 150 tons at 400 CFM per ton. This produces a cost of approximately $6,000. The additional $4,000 is the provision for adjusting the north and south systems to eliminate the high velocity corridor flow on all levels prior to balancing the building's air system.

ABOVE GRADE STAIRWELL MODIFICATION ESTIMATE BASIS

The following basis was used to develop the cost estimate for a typical above grade stairwell reversible flow exhaust system:

1. 833.28 lbs of steel for duct at $1.85/lb, with a total cost factor of 2.25, which results in a total duct cost of: $3,468.53.

2. Six (6) 12" X 12" grilles at $8.13 each and a total cost factor of 1.5 for a total grille cost of $78.17.

3. Preparation for and installation of the reversible air exhaust system for each stairwell:

   a. Material for and installation of a 6" thick concrete pad of 4 square feet: $150.00.

b. Four (4) fan isolators at $25.00 each: $100.

c. Installation of the system with anchor down bolts: $125.

d. Fan cost: $940.

e. Cost of motorized dampers: $500.

f. Roof flashing cost: $397.

g. Overhead and profit margin: $535.

The total cost estimate for installation in the typical above grade stairwell is $2,747.

The total cost estimate for a typical above grade stairwell is $6,300 (rounded).

The total cost estimate for all four (4) above grade stairwells is: $25,000 (rounded).

ABOVE GRADE ELEVATOR HOISTWAY MODIFICATION ESTIMATE BASIS

The following basis was used to develop the cost estimate for the exhaust system that would service all of the above grade elevator hoistways:

1. 1184 lbs of duct steel at $1.85/lb and a cost factor of 2.25, which results in a total cost of: $4,928.40.

2. Six (6) 12" X 12" grilles at $8.13 each and a total cost factor of 1.5 for a total grille cost of: $73.17.

3. Preparation for and installation of the air exhaust system for the above grade elevator hoistways on the roof:

   a. An 8" thick concrete pad of 4 square feet, material and installation: $205.

   b. Four (4) fan isolators at $25.00 each: $100.

   c. Installation of the system with anchor down bolts: $125.

d. Roof flashing cost: $1,200.

e. Fan cost (22BI Trane or equivalent): $1,600.

f. Overhead and profit margin: $750.

The total estimated installation, material and equipment cost for the above grade elevator hoistways' exhaust system is: $9,000 (rounded).

BELOW GRADE STAIRWELL/ELEVATOR MODIFICATION ESTIMATE BASIS

The following basis was used to develop the cost estimate for the modifications necessary to pressurize the below grade stairwells and elevator hoistways:

1. Four (4) dome fans, as specified, or four fans equivalent to the 10FC Trane utility fan at $338.00 each: $1,352.

2. Wall or ceiling installation of four fans: $2,500.

The total estimated cost to modify the below grade stairwells and elevator hoistways is: $4,000 (rounded).

OPERATION & MAINTENANCE COST CONSIDERATIONS

The air exhaust systems for the above grade shafts and the air pressurizing systems for the below grade shafts will have continuing operation and maintenance costs.

The cost elements for operation of the above grade exhaust systems and the below grade pressurizing systems are as follows:

1. Electric power to operate motors producing a total of 4.5 HP.

2. Mantime to check the rooftop fans during freezing weather on a daily basis to insure that the fans and/or their motors have not frozen.

The cost elements for maintenance of both the above grade and the below grade systems are as follows:

1. Periodic checking of the fans, motors, belts, motorized dampers, etc., by the stationary engineering staff.

2. Periodic lubrication of drive components of the rooftop systems.

3. Approximate biannual replacement of the fan belts on the rooftop systems. This assumes that direct drive fans are used in the below grade shafts.

4. Approximate ten year replacement of the fan units, drive components, motors, motorized dampers and isolators.

Electric Power Cost Estimate

The electric power demands are for a total power consumption of 4.5 horsepower. The use of these small systems may be restricted to cold or cool weather conditions, i.e., when external atmospheric temperatures are significantly below a nominal internal building temperature of 70°F. This would require operation over six (6) months per year. approximately. Assuming a conservative 200 days per year operation at 24 hours per day, continuous use of 4.5 horsepower requires approximately 9.668×10^5 KW per year. Large commercial installation rates are on the order of \$0.0223 per KW. This results in an approximate annual electric power cost of \$22,000 or \$3,600 per month during continuous cold weather.

Mantime for Operation

The building has a full time stationary engineering staff. As a part of their function they should be making daily visual inspections of all equipments. The daily checking of the rooftop systems during freezing weather should not add significantly to the time necessary to check other rooftop equipments. Consequently, this requirement should have little impact on the stationary engineering staff. If protection from precipitation is provided to prevent moisture entry into the rooftop systems, this function could be eliminated.

Annual Maintenance Cost Estimate

Estimates of the annual costs for the above specified maintenance cost elements are as follows:

1. Periodic checking of the systems: \$ 750.00

2.	Periodic lubrication:	$ 900.00
3.	Replacement of drive belts:	100.00
4.	Replacement of motors, fans, motorized dampers, isolators, etc.:	2,000.00
	Total annual maintenance cost estimate:	$3,750.00

Total Annual O & M Cost Estimate

The total estimate for the annual operation and maintenance cost of the five (5) above grade systems and the four (4) below grade systems is approximately $30,000. This includes the write down of the equipment for replacement over a ten year period.

SUBSEQUENT SITUATION

In March of 1985, the engineering firm representing the building owner responded to the limited field investigation, or air survey, of the interior air state of the USIA headquarters building. The position of the firm was that the HVAC system was adequately designed and refused to acknowledge that it wasn't operating as designed. The firm also misinterpreted comments made in the report regarding desirable air pressure relationships between workplaces and their adjacent corridors. They responded by stating that corridors are no longer used as return air plenums, which is well known. They claimed that the system was designed to provide a positive air pressure in the workplaces but ignored the pressure difference measurements which indicated negative relationships on the 5th floor and marginal relationships at all of the other involved spaces.

OUT-OF-BALANCE CONDITION

The engineering firm totally ignored the serious out-of-balance condition existing between the north and south HVAC systems. This was clearly evidenced in the high velocity air flow in the corridors of almost every above grade floor.

STACK EFFECT CONDITIONS

The engineering firm also failed to acknowledge the possibility of stack effect existing within the building under winter or cool weather conditions. This is difficult to understand because it has been shown to exist in at least thirty (30) buildings that have been tested, ranging from four (4) to sixty (60) floors in height. It has also been established and well documented by the Center for Fire Research of the National Bureau of Standards. However, the engineering firm did touch on the sensitive aspect of the extrapolation to winter conditions with limited air behavior data. There is no disagreement with the fact that instituting building modifications on this limited investigation is not necessarily a good management decision. However, it is sufficient to justify the performance of a thorough winter interior air survey of the building, at the very least.

END RESULTS

As a result of the negative response from the engineering firm representing the building owner, the building owner has refused to provide any remedial measures beyond the original extension to the rooftop exhaust stack from the fast food restaurant.

During the 1984-85 winter, additional complaints were received by the USIA Health and Safety Officer as had been predicted.

INSTRUCTOR'S NOTES

This engineering case treats an indoor air pollution problem that is created by the interior air migrational characteristics of multi-story buildings. This problem potentially exists within all such buildings. However, its magnitude is dependent upon the existence and significance of three conditions. These conditions are:

1. A source or sources of air pollutants.

2. The interior air leakage properties of a building.

3. The manner of management and maintenance of a building's forced air system.

In general, heating, ventilating and air conditioning (HVAC) systems are designed to provide good breathable air to occupants. In recent years however, energy conservation and minimum operating cost practices have defeated the design objectives of many HVAC systems.

The practices that have significantly impacted interior air quality and that are commonly encountered are as follows:

1. Substantially or totally closing the outside air intakes to a building's heating, ventilating and air conditioning system.

   a. This is a typical practice that is employed by building operators to minimize the energy, and its related cost, necessary to heat or cool outside air to comfort level temperatures.

   b. The result of such a practice is to minimize the volumetric supply rate of fresh outside air to the interior of a building. Consequently, the dilutional effect of the outside air and its oxygen content are not available to maintain good interior air quality.

2. Reducing, stopping or cycling the operation of exhaust and/or ventilation fans, such as those that are used in garage and parking decks of buildings.

    a. This practice is again employed to minimize energy consumption and reduce operating costs.

    b. Since automobile exhaust gases are of a toxic nature, they should not be allowed to migrate to occupant spaces within a building.

    c. Since garages and parking decks are usually found in the lower levels of a building, they are usually below the cool or cold weather atmospheric neutral plane of a building.

    d. As a consequence, the automobile exhaust gases existent on these decks are in an ideal location for vertical migration to the upper levels of a building under winter or cold atmospheric conditions.

The above two (2) practices are not the only measures used by building owners that may impact a building's interior air quality and allow entrance of buoyant pollutants to occupant spaces. However, they are of first order importance to the quality of indoor air.

PURPOSE

It is the purpose of this case to demonstrate a classic, and contemporary, high rise building indoor air pollution problem. This case also illustrates:

1. The effect that a problem of this type can induce in workplaces of such buildings.

2. An inexpensive and effective approach to eliminating or significantly reducing any hazard presented to occupants in such situations.

GENERAL INSTRUCTIONAL OBJECTIVES

The general instructional objectives of this case are as follows:

1. To demonstrate an indoor air pollution problem that can easily exist in state-of-the-art construction, definitely exist in older construction, and that can be an occupational health problem.

2. To illustrate the classic and inadequate present day expertise in attacking and solving indoor air pollution problems.

3. To demonstrate the need for recognizing interior air environments as connected and responsive systems, and in some cases well integrated systems.

4. To demonstrate the dynamic and migrational characteristics of interior air environments, beyond that due to any existing HVAC system(s).

5. To provide the fundamentals of interior air movement and migration behavior that act as transport mechanisms for gas and buoyant particulate pollutants.

6. To identify the indicators that provide insight to an investigator in identifying migrational paths, transport mechanisms and, possibly, sources of pollutants.

7. To provide investigative and evaluative procedures that can be used by all related professions and disciplines, i.e., from qualitative procedures for the non-analytic investigators to detailed quantitative and analytic procedures for the in-depth engineering or scientific investigators.

DISCIPLINE/PROFESSION ORIENTED INSTRUCTIONAL OBJECTIVES

Currently there are several professions and/or disciplines that may become responsible for indoor air problems. As indicated above, one of the objectives of this case is to provide an adequate basis for each of these disciplines and professions to properly investigate such problems and to evaluate candidate corrective measures.

These disciplines and professions are widely divergent in their technical background, and their professional objectives. Consequently, detailed and specific instructional objectives vary widely across these disciplines and professions. The professions or disciplines to which this case is applicable include the following:

1. Mechanical engineers responsible for the design of new heating, ventilating and air conditioning (HVAC) systems, the design of modifications to existing HVAC systems, and the determination and solving of interior air environment problems in existing facilities.

2. Architects and building designers responsible for specifying the sealing and fitting of building components which separate interior spaces from each other and which separate interior spaces from the external atmosphere.

3. Safety engineers responsible for the interior air environment in existing workplace facilities.

4. Industrial hygienists responsible for a safe and healthy air environment in workplace facilities.

5. Health and safety officers lacking a rigorous engineering and technical background.

6. Fire protection engineers responsible for insuring safe air environments along emergency egress routes from workplace facilities.

ANALYTIC PROFESSIONS/DISCIPLINES

In the case of the analytic professions and disciplines, the ultimate objective is to provide these persons with knowledge sufficient to:

1. Be capable of planning and conducting detailed and exhaustive investigations of real or potential indoor air pollution situations.

2. Be capable of analyzing and evaluating the results of indoor air pollution investigations.

3. Be capable of developing and designing adequate measures to prevent and/or correct indoor air pollution problems in:

    a. The design of air systems for new facilities.

    b. The design of corrective measures for inclusion in existing facilities.

Mechanical Engineers

Because of professional engineering practices and the fundamental physical principles, the primary responsibility for new construction design, alteration, addition or modification design to existing construction and the evaluation of identified problems in existing construction for interior air environments rests with mechanical engineers. Consequently, the engineering profession that should and, eventually, must fully understand the dynamics of a facility's interior air environment is the mechanical engineering profession.

Field work over the years has evidenced, in new construction already granted use/occupancy permits, many air system related problems that should have been identified and corrected prior to the granting of the permits. Such problems include wiring large return air fans backwards electrically in a high-rise office building. This type of problem is of a workmanship nature but should have been easily identified prior to the granting of the occupancy permit. An example of a serious air system design problem was found in a large number of mid-rise buildings. Transfer registers were designed too small in area. This resulted

in air being pumped from wall cavities and then distributed throughout each occupant space by each space's individual air supply system. Numerous other air environment problems have been observed that fell within the responsibility of the designing mechanical engineer.

For mechanical engineers, this engineering case is directed toward:

1. Correcting existing indoor air pollution problems.

2. Employing reasonably rigorous field test and evaluation procedures. Test and evaluation practices currently existing are weak, at best. Test and acceptance of a facility's HVAC system and related equipments, in many jurisdictions, remains with the designing engineering and architectural firm. Such tests are often of a perfunctory nature and seldom go beyond a cursory functional check of the equipments.

3. Providing an understanding of the actual behavior of air within a facility, beyond that which moves through the various forced air systems and sub-systems. There are many factors that enter into the behavior of a facility's interior air environment that are presently assumed to be seasonally constant or of little significance, as compared to the HVAC system.

Specific Instructional Objectives - Mechanical Engineers

The specific instructional objectives of this case for mechanical engineers are as follows:

1. To demonstrate and justify the behavior of air within a facility that occurs independent of the HVAC system and in conjunction with that system.

2. To present typical causes of undesirable interior air behavior.

3. To present measures which will prevent typical undesirable behavior for both new and existing construction, dependent upon the nature of either expected or existing causes.

4. To provide a methodology for the conduct of meaningful field investigations in existing construction, including the application and use of appropriate test and measurement devices and equipments.

5. To provide an understanding of how to analyze and evaluate collected field data and information.

6. To provide a methodology for extrapolation of measured and collected data to different air environment state, such as seasonal states.

7. To provide a basis for the identification of effective corrective measures and the criteria for selection and design of appropriate corrective measures.

Safety Engineers

Presently, practicing safety engineers have a wide variety of educational backgrounds. It is not a coherent profession. Many persons practicing this profession are seriously lacking in analytic capability. However, if it is assumed that a formal curriculum exists for this profession, the physical fundamentals and the level of detail provided to the safety engineer should be the same as that presented to the mechanical engineer.

Persons practicing in this profession should have a sound understanding of the cause and effect relationships in the behavior of a facility's interior air environment. They should also have the technical ability to measure and evaluate the condition and state of interior air environments, at their own discretion.

This case presents the safety engineer with many aspects of indoor air pollution problems, i.e., as would typically be encountered in practice. The instructional objectives for the safety engineer are identical to those presented above for the mechanical engineer excepting the design related objectives. The typical practicing safety engineer will not be allowed to design a corrective or preventive measure for indoor air pollution problems. Normally, this can only be accomplished by a licensed mechanical engineering firm. However, safety engineers should be technically capable of evaluating the suitability and

adequacy of the designs of corrective and preventive measures.

Specific Instructional Objectives - Safety Engineers

The specific and key instructional objectives of this case for safety engineers are as follows:

1. To provide a methodology for the conduct of appropriate interior air behavior investigations.

   a. To define appropriate and adequate interior air measurement and sampling sites within a facility.

   b. To select suitable air measurement and test equipments and instrumentation.

   c. To collect and record necessary data and information.

   d. To analyze, evaluate and determine the implications of collected data and information, considering all significant effects.

   e. To identify, from the results of a field investigation, correctable deficiencies in a facility's interior air system.

2. To evaluate corrective or preventive measures.

   a. Prior to their implementation.

   b. Subsequent to their installation.

Fire Protection Engineers

The fire protection engineer's responsibility normally exists only in the prevention, control and suppression of fires within a facility. The fire protection engineer will not typically have any concern with the normal interior occupational air environment of a facility. However, new building and fire codes will soon, if not already, in some cases, require that safe breathable air must be provided along emergency egress routes within a facility during a fire.

The significance of this case to the fire protection engineering profession is in its demonstration of the causes and effects of non-HVAC system related air movement

within a facility. In general, HVAC systems should not operate during a fire, except for smoke control modes of operation. This results in non-HVAC system air movement forces and behavior becoming dominant within a facility. This is particularly true of thermal buoyancy force driven air, whether in a hot or cool combustion situation. Also, the interior effects of external winds cannot, or should not, be ignored during a fire.

Specific Instructional Objectives - Fire Protection Engineers

The specific and key instructional objectives of this case for fire protection engineers are as follows:

1. The relationship between a facility's interior air migration properties.

2. The relationship of a building's exterior envelope to its interior air behavior.

3. The effect of thermal forces on interior air behavior.

4. The impact of a facility's interior air behavior on the protection of emergency egress routes, e.g., stairwells.

5. The fundamental principles involved in protecting the air environment of emergency egress routes during a fire.

Additionally, the same instruction objectives treating investigation, analysis, application and design for mechanical engineers are appropriate to fire protection engineers, except that they would be limited to their area of responsibility.

NON-ANALYTIC PROFESSIONS/DISCIPLINES

In the case of the non-analytic professions and disciplines that may become responsible for indoor air environments, the ultimate objective is to provide these persons with knowledge sufficient for them to insure that such problems in indoor air pollution are properly identified, and properly and adequately resolved.

Industrial Hygienists/Health and Safety Officers

Industrial hygienists and others that will or are practicing in the field of health and safety may not have a background in the physical sciences, e.g., in fluid dynamics and thermodynamics. Consequently, the instructional objectives are substantially different than those described above for some of the engineering professions.

Specific Instructional Objectives - Non-Engineering

The specific and key instructional objectives of this case for the non-engineering professions are as follows:

1. To bring these persons to a state of awareness of the problem area and its characteristics.

2. To provide them with a basic understanding of the cause and effect relationships involved, such as, seasonal dependence, building leakage properties, buoyancy forces, etc.

3. To provide them with the knowledge of the proper steps that should be taken to:

   a. Determine if such a problem exists.

   b. Determine the nature of the problem, if it exists.

   c. Insure that suitable preventive or corrective measures are instituted.

   d. Evaluate the effectiveness of the preventive or corrective measures instituted.

The general objective is to provide these persons with sufficient knowledge to accomplish the above steps in a management sense, not necessarily to perform the steps technically.

A set of slides (based on figures used in the case) is available for purchase from:

Elder Photographic, Inc.
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